DENDROCLIMATOLOGY AND DENDROECOLOGY OF THE DOMINANT CONIFEROUS TREE SPECIES IN EASTERN LABRADOR, CANADA

A. DEAN DUMARESQ

Dendroclimatology and Dendroecology of the Dominant Coniferous Tree Species in Eastern Labrador, Canada

by

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Abstract

Eastern Labrador is a region in Canada relatively unexplored both ecologically and climatologically. In light of recent extensive dendroclimatic and dendroecological studies conducted in the northern and western regions of Labrador, eastern Labrador represents the last area in a contiguous sampling grid across this large forested area. This thesis fills this gap by employing similar sampling and analytical methods to other studies in adjacent regions in order to form strong analytical tools that are applicable both on a local and regional scale.

This thesis employs a systematic sampling grid consisting of three north-south transects and four east-west transects. Two tree-ring chronologies were developed from the dominant species present at each node. In total eight chronologies of black spruce (*Picea mariana* (Mill) B.S.P.), nine chronologies of balsam fir (*Abies balsamea* (L.) Mill), two chronologies of white spruce (*Picea glauca* (Moench) Voss) and one chronology of eastern larch (*Larix laricina* (Du Roi) K. Koch) were developed.

This thesis is centered on two manuscripts. The first is focused on the radial growth-climate relationship of the dominant tree species in eastern Labrador. This study identifies four distinct zones of growth response; the 'maritime zone', a continuance of a zone already identified in western Labrador; the 'subarctic zone' a continuance of a zone identified in northern Labrador; the 'hyper-maritime zone' a previously unidentified zone in southern Labrador; and the 'upland maritime zone' also a potential zone previously unidentified zone along the southeastern coast of Labrador.

The second manuscript is focused on spruce budworm (*Choristoneura fumiferana*) outbreaks in eastern Labrador. This study identifies three major outbreaks in eastern Labrador in 1930s, 1950s and the 1970s. These outbreaks are consistent with regional outbreaks in eastern Canada, and are found to be moving in a west-to-east dispersal pattern from eastern Quebec, through western Labrador and finally into eastern Labrador.

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Chapter One

Introduction and Overview

Dendrochronology is the study of events through time recorded in tree rings (Speer 2010). By analysing the variation in the radial growth of trees we are able to examine the environment in which the tree grew. This is useful in climatological and ecological studies because each ring, as a repository of this environmental information, may be incorporated into data sets that contain records of many types of past environmental conditions. This information is particularly useful for remote locations and temporal periods prior to instrumental records.

Dendroclimatology is a sub-discipline of dendrochronology that uses the principles of dendrochronology specifically for climatic studies (Kaennel and Schweingruber 1995). It is particularly useful in regions like Labrador (Figure 1.1) where climate stations are relatively sparse and many records are incomplete due to missing data or relocation of climate stations. Dendroecology is also a sub-discipline of dendrochronology and it too has proven useful in ecological studies to uncover evidence of past environments and disturbances such as insect infestations and forest fires (Kaennel and Schweingruber 1995).

1.1. Literature Review

The first dendrochronolgical studies conducted in Labrador mostly consisted of point location studies with limited capabilities for spatial analysis (e.g. Cropper and Fritts 1981, D'Arrigo et al. 1992, Schweingruber et al. 1993, Payette 2007). These early studies mainly sampled white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies*

balsamea (L.) Mill) and focused on connections to sea surface temperatures and climate at the limits of tree growth in eastern North America.

A recent emphasis in dendrochronological studies in Labrador has brought regional-scale studies to the forefront. Labrador has now become an area of extensive dendrochronolgical study, with the notable exception to this point being eastern Labrador. More spatially comprehensive studies have been conducted within Labrador by Trindade (2009), Nishimura (2009), and Kennedy (2011). Trindade (2009) examined shifting climate sensitivity of black spruce (*Picea mariana* (Mill.) B.S.P.) and white spruce across an east-west transect through the center of Labrador. She found radial-tree growth limited by temperature, mostly in the summer months of the growth year. Along the coast, Trindade (2009) found a muted climate sensitivity in the trees. She attributed this to reduced solar radiation due to increased fog along the coast. Trindade (2009) also found a transition in climate sensitivity to a more continental climate along the Redwine Mountains approximately 300 km from the coast of the Labrador Sea.

Nishimura (2009) expanded on Trindade's (2009) transect method extending it into a gridded network of sites that included a pattern of nodes in north-south and east-west directions. From this work, Nishimura and Laroque (2011) identified regions of similar radial growth response in conifer species in western Labrador. Specifically, two zones of growth response were identified. In the western side of their study area contiguous with the Quebec border, a 'continental' zone was defined by a positive radial growth relationship to June and August temperatures. In central Labrador, the eastern portion of their study network, a zone with a 'maritime' influence was identified with a positive relationship to July temperatures (Figure 1.1).

Nishimura and Laroque (2010), using the same gridded network of sites, also investigated past larch sawfly (*Pristiphora erichsonii)* outbreaks with a host/non-host analysis. Nishimura (2009) was also able to investigate past spruce budworm (*Choristoneura fumiferana* (Clem.) (Lepidoptera: Tortricidae)) outbreaks across his grid in western Labrador. The study found several large synchronous spruce budworm outbreaks, one between the 1940s and 1950s and another in the 1970s. One critical aspect of this study was that he had no non-host species to define his budworm outbreaks (Nishimura 2009). In the host/non-host method, a non-host is a species of tree whose pattern of radial growth is determined by the same environmental controls as the study species, yet this non-host species is not susceptible to defoliation by spruce budworm (Speer, 2010). The non-host species is used as a control to allow observation of radial growth depressions in the host species that are not seen in the non-host species. Nishimura (2009) derived his outbreak data using a new, perhaps less robust method, that incorporated an averaged regional mean instead of a non-host chronology (Nishimura 2009).

Kennedy (2011) systematically sampled and studied the treeline region of northern Labrador adding ten more sites to those sampled in Labrador. His work studied white spruce at its northern extremes to observe shifts in its radial growth to climate relationship across treeline. Kennedy (2011) identified two zones that he differentiated by slight differences in ecological tolerances within the climate radial-growth relationships experienced by white spruce at treeline, finding a north-south gradient present. The 'arctic maritime zone,' define solely by June/July temperatures and the 'subarctic maritime' zone that were defined not only by June/July temperatures, but also a

negative response in radial growth to spring temperatures (Figure 1.1). He further projected the radial-growth rates of white spruce at treeline up to the year 2100. He was able to discern that the southeastern portion of the treeline was the most likely part of the treeline to advance north and westward due to future projected climatic changes (Kennedy 2011).

Kershaw and Laroque (2011) changed the overall mode of the dendrochronological investigations by, for the first time, studying a deciduous tree species in Labrador. This study somewhat mimicked the sampling protocol of Trindade (2009) in that it investigated an east-west transect across southern Labrador utilizing the recently completed Trans-Labrador highway corridor. This study identified that the radial growth of trembling aspen (*Populus tremuloides* Michx.) in central and eastern Labrador was responding to climate in a similar fashion to the conifer species in the maritime climate-growth zone identified in Nishimura and Laroque (2010) as a marked response to July temperatures. This 'maritime' effect reached eastward to the extent of trembling aspen stands, before their populations ceased along the coastal barrens on the eastern portions of Labrador adjacent to the sea.

Other than dendrochronological studies, there have been several other studies published on the general environmental characteristics of Labrador. Most notably from these studies is Banfield and Jacobs (1998) who conducted an extensive study of climate, both on Newfoundland Island and Labrador. Their findings revealed trends in temperature and precipitation that related to seasonal North Atlantic Oscillation (NAO) values. Banfield and Jacobs (1998) also found increased variability in interannual winter

temperatures at Cartwright, a coastal weather station, and Goose Bay farther inland. They attribute the Cartwright variability to late winter sea ice which increases the degree of continentality along this coast region. A similar winter continental effect was present in Goose Bay but was attributed to the more southerly position of the polar front during the winter months. This variability in interannual temperature was reduced during summer months. They do not mention the effect of Lake Melville which would freeze during the winter and dampen its effect on the adjacent Goose Bay climate station during the winter. As a general trend in winter temperature, Banfield and Jacobs (1998) found several periods of altered variability from normal levels in Newfoundland and Labrador. Specifically they found cooler periods between 1920-1935, and 1972-1995, with a contrasted warmer period from 1951-1971. The periods of oscillating temperatures were not found during summer months. The only trend identified for summer temperatures was a general overall warming throughout the 20th century.

Ecologically two general studies have focused on eastern Labrador. Roberts et al. (2006) identified Labrador as a boreal and subarctic landmass with an overarching climate forced from the Labrador Current. Roberts et al. (2006), citing Banfield (1981), outlines four environmentally defined regions in Labrador, two of which relate directly to this thesis. The first was the 'southeastern interior Labrador' region, which is less continental than areas to the west, but has a greater amount of precipitation than other regions in Labrador. The second is the 'coastal Labrador' region, which is defined as a region with less continental characteristics, less precipitation than the interior, and cold onshore circulation.

Foster's (1984) study intensively enumerated vegetation in southeastern Labrador. Within this portion of Labrador, five forest types were classified; (1) birch; (2) fir - spruce - feather moss; (3) spruce-fir; (4) spruce-*Pleurozium*; and (5) spruce – *Sphagnum fuscum* communities. Within this region Foster (1984) identified the black spruce – balsam fir forest as encompassing more than 95% of the forest canopy. These stands form a broken canopy at approximately 15 metres high, with a generally open understory.

1.2. Research Questions

The recent activities in dendrochronological research in Labrador have provided a significant foundation for spatial analysis across a regional scale of sampling transects and networks (e.g., Nishimura and Laroque 2010, Trindade et al. 2011, Kennedy 2011). Although these studies have aptly investigated much of Labrador, a significant area in the eastern portion of the region remains unexplored. This thesis aims to complete the network by infilling the area between Kennedy (2011) and Nishimura and Laroque (2010, 2011), thus completing the sampled network of all forested regions of Labrador. The aim is to place eastern Labrador into the context of the radial growth-climate response zones already established in other locations of Labrador. Specifically this thesis asks; does eastern Labrador exhibit the same radial growth response zones that extend outside the boundaries of previous studies, or do the trees in eastern Labrador exhibit a different set of radial growth-climate trends?

With recent dendrochronological advancements in the study of the first deciduous species in Labrador from Kershaw and Laroque (2011), this thesis will also explore the potential of these new chronologies to aid in the knowledge of past insect outbreaks

within conifers in eastern Labrador. This opportunity holds the potential of a better understanding of natural cycles in ecological disturbances in the vast region of eastern Labrador. It also provides an opportunity to compare results against Nishimura's (2009) analysis in order to observe these disturbances at the greater Labrador scale. This new research may also help overcome the hurdle that Nishimura (2009) encountered of an absent non-host species to identify spruce budworm outbreaks in Labrador. The spruce budworm study in this thesis also concludes the last large region to be explored in an attempt to understand the past ecological characteristics of one of the most important insect defoliators in the boreal forest of eastern Canada. It fills the one remaining unexplored area in an interprovincial-scale scope of spruce budworm disturbances in boreal eastern Canada.

1.3. Manuscript Approach

This thesis is written in a manuscript style with two manuscripts at its core. The aim of the first manuscript is to explore the radial growth–climate sensitivity across a gridded network of nodes in eastern Labrador. This manuscript will employ response function analyses using bootstrapped correlations to identify the dominant climate factor influencing radial growth in the dominant coniferous tree species of eastern Labrador.

The aim of the second manuscript is to explore the temporal and spatial trends of past spruce budworm outbreaks across the same eastern Labrador nodal sampling grid as the first manuscript. This manuscript employs a host/non-host analysis to identify radial growth reductions caused by defoliation in tree species susceptible to spruce budworm activity. Taken as a whole, the two manuscripts aim to help fill in the gaps and complete a

regional picture of past ecological and climatological characteristics of the forests of Labrador. These studies aim to identify patterns bridging scales from the site-specific, to the regional and even inter-provincial scale in order to aid in identifying the major controls on forest development in eastern Labrador.

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1.5. Figure Caption

Figure 1.1 Map of Labrador with inset of North America and approximate boundaries of the four zones of radial growth-climate relationships. The 'continental zone' and the 'maritime zone' were defined by Nishimura (2009). The 'arctic maritime zone' and the 'subarctic maritime zone' were identified by Kennedy (2011).

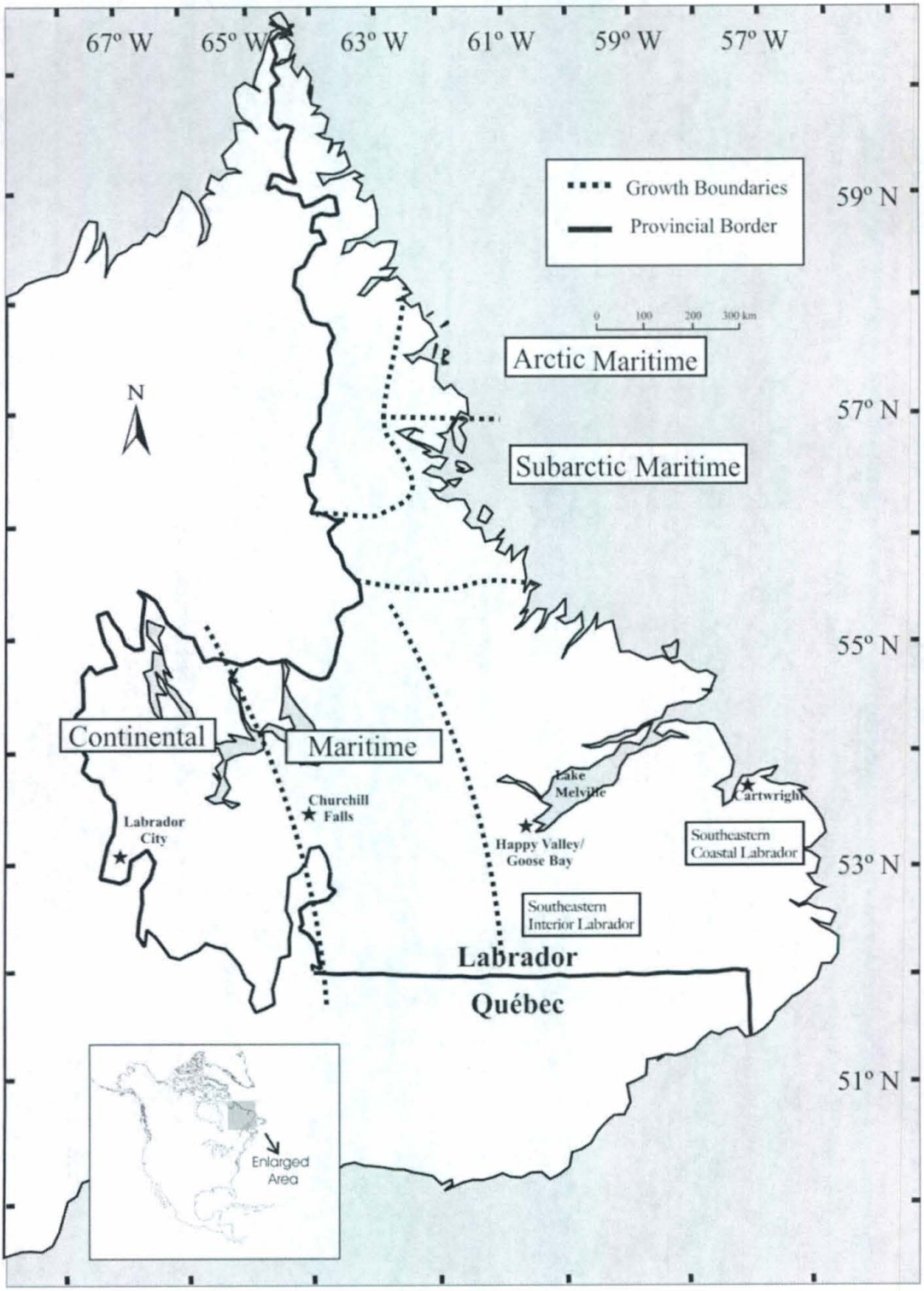
67° W
65° W
63° W
61° W
59° W
57° W
59° N
57° N
55° N
53° N
51° N
Growth Boundaries
Provincial Border
0 100 200 300 km
N
Arctic Maritime
Subarctic Maritime
Continental
Maritime
Churchill Falls
Labrador City
Lake Melville
Happy Valley/ Goose Bay
Cartwright
Southeastern Coastal Labrador
Southeastern Interior Labrador
Labrador
Québec
Enlarged Area

Figure 1.1

Co-authorship Statement

The design and development of the research proposal were completed by me, with input from Colin Laroque and Trevor Bell;

The practical aspects of the research were completed by me, with logistical support by Colin Laroque, Trevor Bell, and Mariana Trindade;

All data analysis was completed by myself;

All manuscript preparation was completed by me with comments and editorial suggestions from Colin Laroque and Trevor Bell.

Chapter Two

Tree-Ring Radial-Growth Relationships to Summer Temperature Across a Network of Sites in Eastern Labrador

Dean Dumaresq[1], Colin P. Laroque[2] and Trevor Bell[1]

[1]Department of Geography

Memorial University of Newfoundland

St. John's Newfoundland, Canada.

A1B 3X9

[2]Mount Allison Dendrochronology Laboratory

Department of Geography and Environment

Mount Allison University

Sackville, New Brunswick E4L 1A7

Phone (506) 364-2390, Fax (506) 364-2625

E-mail:

ddumaresq@mun.ca

claroque@mta.ca

tbell@mun.ca

2.1. Abstract

This study uses a dendroclimatological analysis to observe spatial shifts in the radial growth-climate relationships of conifer species across southeastern Labrador. Ten sites were sampled across a systematic grid consisting of three north-south transects and four east-west transects all spaced approximately 100 km apart. Chronologies included black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill), white spruce (*Picea glauca* (Moench) Voss) and eastern larch (*Larix laricina* (Du Roi) K. Koch). They were developed from the dominant species present at each node. Pearson product moment correlations and response function analyses were utilized to identify four zones of radial growth-climate relationships within the study area; the 'maritime zone', extending from the west, defined by a strong relationship to July temperatures; the 'hyper-maritime zone' along the eastern coast, defined by an extended growing season in balsam fir; the 'subarctic maritime zone' in the north defined by a June/July temperature relationship; and the possibility of the 'upland maritime zone' in the south, defined predominantly by an ecological shift from fir to larch. Distinctions in the growing seasons illustrates a radial growth-climate gradient from west to east and a north-south gradient is also present in the northern regions of the study area.

2.2. Introduction

Vincent and Gullett (1999) noted that northern climate stations are sparse in spatial extent compared to more southern regions and they also cover a much shorter time span. With scant instrumental records available in these more remote areas, it is necessary to develop proxy records in order to gain a better understanding of how past climates relate to ecological processes (Delworth and Mann 2000), especially in these northern areas where the most rapid changes in climate have been recently noted (Raisanen 2001, Hassol, 2004, Johannessen et al. 2004, Chapin et al. 2005, Trenberth et al. 2007). By investigating the radial growth-climate relationships of trees across a broad region, tree-ring analysis studies typically build the foundation for broader scale palaeoecological and palaeoclimatological studies in a region where little research has been conducted and few data records exist.

Early tree-ring studies in Labrador concentrated their efforts in mostly a few locations in the northeastern region of Labrador (e.g., Cropper and Fritts 1981, D'Arrigo et al. 1996, Schweingruber et al. 1993, and Briffa et al. 1994). Although useful in their own right, these studies lacked a larger scale comparative perspective that newer studies have incorporated in their design (e.g., Payette 2007, Trindade 2009, Nishimura 2009, Kennedy 2011), which have been better at unravelling many of the complexities of the paleoclimate and ecology of the Labrador region.

Payette (2007) was the first to illustrate a shift in dendrochronological studies in the region from a single point study to a larger, more comparative, regional assessment.

This seven site study was also the first to identify a shift in tree responses between coastal and inland regions of Labrador. The study focused on northern Labrador's latitudinal treeline from the coast into the adjoining province of Quebec. It found a distinctive difference between the inland white spruce (*Picea glauca* (Moench) Voss) growing at treeline in Quebec, which has receded over the past centuries (Lamb 1985, Payette 2007), and coastal locations in Labrador where the treeline had advanced. Payette (2007) attributed this to both climate changes and bio-geographical influences of the rugged coastline and drastic shifts in topography. This likely has caused the lagged migration of treeline northward in the post glacial landscape.

Trindade's (2009) research illustrated a shift of sensitivities between tree-ring radial growth and associated climates of central Labrador. The study found changes on both a spatial and temporal basis, tied closely to the proximity of a tree's location to the coast. The study utilized a longitudinal transect extending from coastal Labrador near Cartwright and reached westward as far as Labrador City, 670 kilometres to the west (Figure 2.1). Trindade (2009) found a shift in responses across the transect and speculated that parameters such as fog influenced the amount of solar insolation available to trees growing in the near-coastal areas that helped distinguished their radial growth from inland sites. She hypothesized that fog along the coast could account for a dampened July sensitivity as it would block the solar radiation. She theorized that dissipation of fog caused by higher temperatures was in fact responsible for the more favourable growing conditions, rather than a direct causal relationship between temperature and radial growth in coastal regions. Trindade et al. (2011) investigated the temporal nature to the climate-

radial growth relationship over the same transect as Trindade's (2009) research. They found shifting climate to radial-growth relationships over the past century closely related to changes in precipitation.

With support from the International Polar Year, recent studies have established a large scale, spatially systematic sampling approach for dendroclimatological studies in Labrador (e.g. Nishimura and Laroque 2011, Kennedy 2011). By expanding the Trindade (2009) transect sampling model across central Labrador, these studies attempted to better understand any spatial shifts in the climate sensitivity of the trees at a greatly refined and contiguous scale than previous studies have attempted in Labrador. The most extensive tree ring investigation in Labrador was recently carried out in the western region by Nishimura and Laroque (2011). This study used a spatial network of dendrochronological sites, creating a grid of north-south and east-west transects covering all of western Labrador. The results of this study illustrate a transitional shift in the climate-tree ring relationship as one moves further eastward toward a maritime influence. In particular, the study delineates a transition between two distinct zones. The 'continental zone' defined by tree radial-growth responses to May and July temperatures, and the 'maritime zone', characterized by a radial-growth response to mean July temperature. Nishimura and Laroque (2011) attribute this shift to increased mid-summer temperatures in western/continental regions of Labrador.

Kennedy (2011) furthered the large network by investigating the radial growth-climate relationship in trees at their northern extent of growth in Labrador. He found sparse white spruce stands growing in the protection of low-lying land, near bodies of

water. The radial growth response of trees within these pockets, isolated by barrens, was primarily defined by a correlation to June/July temperatures. A distinction was drawn between northern sites, in an 'arctic maritime zone', define solely by June/July temperatures, and a 'subarctic maritime' zone that was defined not only by June/July temperature, but also a negative response in radial growth to spring temperatures. This negative response to spring temperatures is attributed to springtime desiccation caused when the photosynthetic processes commence before the active layer thaws, which restricts the tree's access to moisture.

These above recent dendroclimatic investigations in Labrador have revealed gradients of shifting climate to radial-growth relationships across the region (e.g. Nishimura and Laroque 2011, Kennedy 2011, Trindade et al. 2011). With well-defined zones delineating the dominant climate controls in the majority of Labrador, eastern Labrador represents the last significant gap in this body of research. This region has been left relatively undefined in terms of the how the spatial patterns of climate to radial growth relationships exist within southeastern Labrador, and in relation to its contiguous regions.

The main purpose of this study is to better understand the spatial nature in the radial growth characteristics of the tree-ring and climate relationship of the dominant conifer species in southeastern Labrador. Specifically, this study predicts that the radial growth-climate relationships identified in other regions of Labrador extend into eastern Labrador, and that due to the adjacent Labrador sea, the radial growth-climate

relationships in southeastern Labrador shift due to increased temperature changes as one approaches the coast.

2.3. Study Area

The study area encompasses the entire southeastern region of Labrador. The area has a varied topography, climate and ecology. In past studies, three zones have been delineated by topographic and climate characterises in the region. An upland area (Foster 1984), the 'southeastern interior Labrador' zone, and the 'coastal Labrador' zone, (Roberts et al. 2006). A fourth broad zone, not previously delineated, is defined in this study to the north of Lake Melville.

The topography within the study region ranges from lowland regions along the coast, to higher ground on the Eagle and Lewis Plateaus (Figure 2.1) in southeastern portion of the region. These plateaus help define an upland region that runs in a north-south direction approximately 100 km west of the southeastern Labrador coast. Elevation in this region ranges up to 670 metres above sea level. In the center of the study region is Lake Melville which transects the study area in an approximate east-west direction. The Mealy Mountains, with peaks approximately 2000 metres above sea level, rise to the south of Lake Melville and to the northwest of the Eagle Plateau. The 'south eastern interior region' (Foster 1984) is the remaining area to the south of Lake Melville and to the west of the uplands. This region is fairly homogeneous with elevations ranging from 300 to 400 metres above sea level. To the north of Lake Melville, the landscape resembles more closely the landscape observed by Kennedy (2011). It is a fairly flat

elevated region dropping into fjord-like coastline valleys. The coastal areas in the southern regions do not exhibit the same dramatic fjord-like terrain as the northern coast in the study region.

Climate studies in the region indicate Labrador to be particularly influenced by maritime forcings (Banfield and Jacobs 1998). The longest continuous climate stations in or near the study area are found in Cartwright and Goose Bay (Figure 2.1). The Cartwright average annual temperature is -0.5 ˚C and average annual precipitation is 583 mm. Figure 2.2 illustrates mean monthly temperature of both the Cartwright and Goose Bay stations over the entire common record of the climate stations. Due to its relative inland location, Goose Bay illustrates higher average summer temperatures and a sharper decline to colder temperatures from August to December, than what is recorded at the Cartwright station as it is positioned adjacent to the Labrador Sea (Figure 2.2). Banfield and Jacobs (1998) found these stations to exhibit substantially less variability in winter temperatures with muted variability in the summer.

Labrador precipitation on the other hand was attributed to convection or conditional instability in interior areas in the summer months. This instability is common along coastal regions during fall and early winter months when cold continental air masses interact with warmer air over open waters (Banfield and Jacobs 1998). Upland regions in the southeast are characterized by greater precipitation than most other regions in Labrador. The costal region is defined by less precipitation than the interior, because it is subjected to cold onshore circulation patterns (Roberts et al. 2006).

Ecologically the majority of the region is dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill) (Roberts et al. 2006). Other species present in the area include white spruce, eastern larch (*Larix laricina* (Du Roi) K. Koch), trembling aspen (*Populus tremuloides*(Michx.)) and paper birch (*Betula papyrifera* (Marsh.)) (Foster 1984). In 'southeastern interior Labrador' the black spruce and balsam fir forests that dominate the landscape are slow growing caused by semi-permanently frozen soil and short growing seasons (Foster 1984). Poor soil drainage is the dominant factor that influences soil type and thus vegetation habitat and diversity of the 'uplands' in southeastern Labrador. Here a thick organic peat soil caused by this poor drainage (Roberts et al. 2006) help support the black spruce and co-dominant eastern larch forests, rather than balsam fir present in other regions of eastern Labrador (Foster 1984).

The southern coastal areas are mostly barren with young stands of black spruce and fir present only in low lying sheltered areas because of a lack of protection from winds off of the open sea. Black spruce in particular grows in valleys when it is near its climatic tolerance and seed regeneration tends to be more sporadic (Payette et al. 1982). The salt intolerance of black spruce causes a particular difficulty propagating in regions with greater salinity concentrations. Toxicity symptoms due to this intolerance, including shorter rooting structures, make the trees more susceptible to wind loads (Croser et al. 2000). The younger stands are also likely related to an increased and unpredictable fire regime in this region of reduced peat lands and varied topography (Foster 1983).

The northern region was defined by isolated forest stands along the coast in low lands and barrens with more contiguous forested regions inland. Balsam fir begins to become sparse in this area, as it reaches its northern limit in these portions of Labrador (Roberts et al. 2006). White spruce also begins to take the place of black spruce as the dominant species in these parts of the region (Roberts et al. 2006).

2.4. Methods

A systematic gridded sampling protocol was applied across the entire eastern portion of Labrador. Each site was selected at the closest accessible point at the intersection of 52, 53, 54, and 55 degrees north latitude and 56, 58, and 60 degrees west longitude (Figure 2.1, Table 2.1). A similar spatial framework and resolution was applied in western Labrador by Nishimura (2009). The node at 55 degrees north latitude and 62 degrees west longitude rested immediately adjacent to the coast in its theoretical position (Figure 2.1). For practical reasons it was sampled to the southwest of the theoretical node point in the nearest forest. Two nodes at the intersections of 54 and 55 degrees north latitude, with 60 degrees west longitude rested over the Labrador Sea and were eliminated from a completed grid square leaving only the remaining 10 nodes on land to be sampled (Figure 2.1).

Each node was labelled according to their position in the grid. The nodes were labelled by column, with a "W" designation used for the most westerly nodes, a "C" used to designate the central column, and an "E" used to designate the most easterly nodes (Figure 2.1). In the north-south direction, a numerical system was applied. The most

northern row of nodes were designated as 1, and then each row was sequentially numbered until the most southern row, which was labelled as 4 (Figure 2.1).

The sites can also be classified from their geographic location. Nodes that were not sampled near the coast (W2, W3, W4, C2, C3) were inland nodes. Sites within close proximity (maximum of ten kilometres) to the open coast of the Labrador Sea (E3, E4) are considered 'coastal Labrador'. Node C4 rests on the Lewis Plateau (Foster 1984) and thus is considered an upland node. The northernmost nodes, which border between coastal barrens and high subarctic tundra were considered subarctic sites (W1, C1) (Roberts et al. 2006).

At each node, the two most co-dominant tree species were selected and sampled following the protocols of Trindade (2009) and Nishimura (2009). Two increment cores were extracted at breast height from 20 mature trees from each species for a total of 40 cores per species, 80 cores per node. The cores were brought back to the Mount Allison Dendrochronology Laboratory, glued into slotted mounting boards, sanded to a fine polish, and visually checked for a shared radial-growth pattern. The total annual ring widths were measured with a Velmex system to the nearest 0.001 mm, and then crossdated. The rings were statistically evaluated to check for homogeneity within their radial-growth patterns using COFECHA (Holmes, 1983, Grissino-Mayer, 2001). Each core was divided into 50-year increments overlapping every 25-yrs. These increments were statistically compared through a correlation analysis to the master chronology made up of all cores within a series.

Descriptive statistics generated by COFECHA were analysed to insure the statistical rigour of each chronology (Table 2.1). Mean series intercorrelation (MSI), was used as a measure of the commonality of the radial growth between a core and a master chronology within a set of cores. The MSI was developed by taking the mean of all of the correlation coefficients within a set (Wigley et al. 1984, Trinidad 2009). Segments that did not exceed the mean series intercorrelation threshold above $p>0.01$ (values above 0.3281) were visually checked and corrected using pointer years (exceptionally narrow or wide rings used as waypoints within a pattern) (Table 2.1). Average mean sensitivity (AMS) was used to analyse the relative change in ring width on an interannual resolution (Fritts 1976). Autocorrelation (AC) is a measure of the autoregressive structure within a series. This is commonly seen in radial-growth series due to the influence of the environmental conditions in a previous growing season that affects the radial growth of the tree in the next year (Briffa and Jones, 2001).

In order to eliminate non-environmental growth signals present in individual trees, each chronology was standardized. Using the computer program ARSTAN, a single detrending negative exponential curve, similar to that used by Trindade et al. (2011), Nishimura and Laroque (2011) and Kennedy (2011), was fit to each series (Cook 1985; version ARSTAN_41d). The program was also used to average all of the cores in a series down into a master chronology by using a weighted mean function (Cook 1985).

DENDROCLIM2002 (Biondi and Waikul 2004) was then used to run a response function analysis on each chronology. DENDROCLIM2002 uses bootstrapped correlations to analyze the annual radial-growth response to climate factors that may be

influencing radial-tree growth. The analysis was run using a sampling window of 18 months. The window starts in April of the previous year (t-1) and ends in September of the growth year (t=0). This window was selected based on the growing season of the sampled species and the climate data available in the region. A similar window was used by Nishimura and Laroque (2011) and Trindade et al. (2011).

2.5. Climate Data

Two Environment Canada climate stations are located at the eastern and western margins of the sampling grid: Cartwright to the east and Goose Bay to the west (Figure 2.1). The common interval of study record for the two climate stations is 65 years, from 1942 to 2006. Although other known stations are within the greater region [e.g., Hopedale on the coast approximately 50 km north of node C1; and Battle Harbour, which was moved in 1983 to near Mary's Harbour, on the coast approximately 30 km north of node E4 and 80 km south of E3; (Figure 2.1)], these records are short and discontinuous due to relocation and/or missing data.

The Cartwright station data were solely used for climate analyses in this study. The location of Goose Bay was outside of the western edge of the study region and, although it was within close proximity the western sites it was deemed too distant from the eastern nodes of the gridded network. Conversely, Cartwright is central to all nodes within the network of study sites.

2.6. Results

Of the 20 sampled chronologies, eight were black spruce, nine were balsam fir, two were white spruce, and one was eastern larch (Table 2.1). The average length of each increment core within the total sample population was 111 years. The coastal nodes (E3 and E4) with mean ages of 72 years tended to be much younger than those farther inland (Table 2.1). The northern sites (W1 and C1) had slightly older chronologies with an average age of 109 years, mostly due to the length of the white spruce chronologies. The interior sites and the upland site were of similar age with an average of 124 years.

2.6.1. *Correlation Analyses*

Table 2.2 presents the results of an interseries Pearson's product moment (r) correlation between all 20 chronologies. The strength of the significant positive correlations ranges across the sampling grid from 0.22 to 0.88 (n=90; all values above 0.21 have $p>0.05$ level). There are significant correlations between most chronologies at most nodes (130 of 190 combinations, 68%), particularly between western and central nodes. Most of the 60 non-significant correlations between chronologies occur between different species (n=47, 78%), while the non-significant correlations between the same species occur exclusively at coastal nodes. These results illustrate that there is a high degree of similarity in growth patterns between all chronologies of the same species, particularly inland of the coastal nodes. In light of this, we conducted a response function analysis to better understand the role of climate, the most likely overriding effect on radial-tree growth in the region.

2.6.2. Response Function Analyses

Tables 2.3 and 2.4 identify significant correlations between the 20 chronologies and mean monthly temperature for Cartwright over the 18 months test period for two significance levels: $p>0.05$ and $p>0.01$, respectively. At $p>0.05$, July temperature of the growth year is consistently correlated with radial growth for all 20 chronologies (Table 2.3), whereas at $p>0.01$ neither the coastal nor upland sites are significantly correlated and only W1, W2 and C3 are correlated across all measured species. Nodes W3, W4 and C2 are significantly correlated for black spruce and C1 for balsam fir chronologies only (Table 2.4).

At $p>0.05$, white spruce is significantly correlated with mean June and September temperature of the current growing season only at the two northern nodes (W1 and C1), whereas at the $p>0.01$ level, only white spruce at C1 retains a significant correlation with mean September temperature. Both balsam fir at the two coastal nodes (E3 and E4) and eastern larch at the upland node (C4) are significantly correlated with mean September temperature at $p>0.01$ (Table 2.4).

At $p>0.01$, black spruce at nodes W2, W3, W4, C2 and C3 and white spruce at W1 are significantly correlated with mean July temperature of the preceding growing season, while at $p>0.05$, balsam fir at nodes W1 and W3 show a similar correlation. Eastern larch at the upland node (C4) has the greatest number of significant correlations with mean monthly temperatures for both the current (n=4) and the preceding (n=5) growing seasons at $p>0.05$, extending from summer to fall months in both years (Tables

2.3 and 2.4). Balsam fir is significantly correlated ($p>0.05$) with mean October temperatures of the preceding growing season at the two coastal nodes.

2.7. Discussion

As observed in other studies in the region the dominant factor in the radial growth-climate relationship is July temperatures in the year of growth (e.g. D'Arrigo et al. 2003, Payette 2007, Nishimura 2011, Kennedy 2011). The 'maritime zone', previously identified by Nishimura and Laroque (2011) is solely defined by strong radial growth relationship to July temperatures. The significant correlations ($p >0.05$) to July temperatures in western and central columns (W2, W3, W4, C2, C3) of this study denotes an extension of the 'maritime zone' towards the coast. Several of these nodes also exhibit negative growth relationships to April temperatures, which has been identified in other region of Labrador (e.g. D'Arrigo et al. 2003, Kennedy 2011) and is attributed to moisture deficits relating to frozen soils in early spring. If photosynthetic processes commence before the active layer has thawed, trees can desiccate because the moisture is inaccessible in its frozen state (Kennedy 2011).

To the north, the 'subarctic maritime zone' identified by Kennedy (2011) is defined by a June-July growing season with an extension into the fall. The earlier commencement to the growing season and the significant correlation to September temperatures within the white spruce chronologies at W1 and C1 indicate that these nodes are closely related to the 'subarctic maritime zone'. Although Kennedy (2011) typified his sites to be dominated almost exclusively by white spruce and not balsam fir which

was present at W1 and C1, his sites are also well above the 54° northern limit of balsam fir growth (Roberts et al. 2006). The close proximity to the coast and the relatively southern location of the nodes, in relation to the 'subarctic maritime zone', accounts for the slight deviation in transition from the purely subarctic radial growth-climate response zone to the north. Nevertheless it is clear that Kennedy's (2011) defined zone extends southward through a transitional region into the 'maritime zone' illustrated in this study's gridded network.

When the higher significance threshold of 99% was used to analyze July growth responses, a distinction could be drawn which demarcates the nodes in the eastern portions of the study region (E1, E2) with a muted response. This is likely caused by cold onshore air circulating off the Labrador Current which could very well shift the phenological cycle of the trees putting less emphasis on July temperatures. This hypothesis is strengthened by the response to an extended growing season relative to the node farther west as illustrated in these node's response functions (Table 2.3 and 2.4). The interaction of cold ocean currents meeting with a warmer air mass could also be responsible for the increased fog discussed by Trindade (2009) ultimately resulting in this dampened effect. The balsam fir in the easternmost nodes also illustrated a significant relationship to September temperatures which is indicative to a later growing season. These more subtle distinctions in the radial growth-climate relationships from the other nodes in the study region are supported by the interseries correlations which clearly illustrate that the eastern nodes have a similar growth trend to each other, and a dissimilar trend to all other nodes (Table 2.2).

The data also illustrate that the most extreme eastern coastal sites had distinctly younger trees (Table 2.1). There are several possible causes for this division in the data. The first is the general lack of protection near the open sea. Tree stands in easternmost Labrador tended to be found in lower lying areas surrounded by barrens. With little protection from harsh weather condition due to smaller stands constrained mostly to valley bottoms, trees may not have had the chance to mature to the stage observed at the inland sites. Younger stand ages may also be related to the possibility of slow and unpredictable development of forested regions in a post glacial landscape that has recently emerged from isostatic uplift (Rupp et al. 2001, Payette 2007). This effect would be pronounced by increased fire disturbances relative to adjacent areas (Foster 1983), as well as increased salinity causing a particular susceptibility to winds loads (Croser et al. 2000).

The distinctions, in radial growth-climate sensitivity, interseries growth trends, as well as younger stand ages seen in the extreme eastern nodes indicate a radial growth-climate relationship as yet unseen in Labrador. We now title it the "hyper-maritime zone". This zone is limited to the coastal regions of southern Labrador (Figure 2.3) and encompasses nodes E3 and E4.

The geographic location of C4 on the boarder of the Lewis Plateau, the presence of eastern larch and the lack of balsam fir, ecologically place it in the same ecoregion as the plateau uplands (Foster 1984). The larch response extending to fall temperatures roughly corresponds to Trindade's (2009) study, yet her results regarding eastern Larch were rather inconclusive. We hypothesize that the results from this node can be titled the

"upland maritime" radial growth-climate zone (Figure 2.3), but further study of eastern larch and black spruce responses on the Lewis and Eagle Plateaus is required.

2.8. Conclusion

The spatial nature of conifer growth responses in Labrador is complex. This study identifies the continuation of two transitional zones, a new distinct coastal zone and a new possible upland zone of growth response. The eastward continuation of the 'maritime zone' previously identified by Nishimura (2009) extends until approximately 10 km of the Labrador coast where it transitions to the newly defined 'hyper-maritime zone'. This maritime zone is possibly interrupted by the Lewis and Eagle Plateau, where we have also establish evidence of a possible 'upland maritime effect'. The southerly continuance of the 'subarctic maritime zone' defined by Kennedy (2001) now can be extended approximately 100 km south of Postville (Figure 2.3).

Eastern Labrador is unique in the Labrador region as it is best represented as a large transitional area where the greatest number of radial growth-climate relationships within Labrador can be observed. What is clear from this study is that Labrador is characterised by both north-south and east-west gradients and that eastern Labrador contains the convergence of these gradients. The north-south gradient, contained mostly in northern treeline regions and the east-west gradient can now be seen in its entirety as a Trans-Labrador temporal shift in growing seasons in southern regions of Labrador. This gradient can be observed from the western extreme, where conifers in the 'continental zone' commence their growing season in May, shifting to central Labrador, where radial

growth becomes more concentrated in July, again shifting near the coast where the growing season extends into September.

The gridded approach to sampling has provided a strong spatial analysis tool as yet unseen in the southeastern area of Labrador. Combined with the Nishimura (2009) and the Kennedy (2011) data sets, there is now the capability to observe trends in radial growth and ecological growth responses on both the refined spatial scale of specific areas of Labrador, as well as the more general scale of all of Labrador and adjacent areas of the province of Quebec. This information provides the opportunity to expand our knowledge and lend evidence to begin to answer questions such as: How will the 'continental', 'maritime' and 'hyper-maritime' zones of tree growth be affected under the projected changes in the climate of Labrador? Will the 'hyper-maritime zone' begin to experience a heat related stress caused by elevated mid-summer temperatures if the growing seasons continues to warm, or will they continue to lag behind inland areas because of the influences of the cool Labrador Sea (Lazier, 1988)?

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2.9. References

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Table 2.1 The site details of each location and statistics relating each crossdated master chronology. BS = black spruce; WS = white spruce; EL = eastern larch; BF = balsam fir. MSI = mean series intercorrelation (calculated on 50-year lagged segments); MTA = mean tree age; AMS = average mean sensitivity; AC = unfiltered auto-correlation; MM = mean Measurement (annual increment). Eco-region; Based on Newfoundland and Labrador Department of Environment and Conservation, Parts and Natural area Division (see website at http://www.env.gov.nl.ca/parks/apa/eco.html) (Roberts et al. 2006); HST = high subartic tundra; LB = low boreal; HBF = high boreal forest; LSF = low subarctic forest; CB = coastal barrens; MB = mid boreal forest.

Site	Site Name	Species	Latitude	Longitude	Elevation (m asl)	Period and Length (years) of Chronology	No. of Cores	MSI	MTA	AMS	AC	MM	Eco-region	Distance to Coast (km)
W1	Bush Pond	WS	54.8141°N	59.9345°W	28	1666-2007 (342)	36	0.534	156	0.198	0.803	0.43	HST	40
W1	Bush Pond	BF	54.8141°N	59.9345°W	28	1807-2007 (201)	33	0.504	113.8	0.195	0.788	0.43	HST	40
W2	Bug Tussle	BS	53.8849°N	60.0025°W	283	1751-2007 (257)	34	0.525	199.6	0.189	0.82	0.41	LB	170
W2	Bug Tussle	BF	53.8849°N	60.0025°W	283	1845-2007 (163)	34	0.47	117.3	0.205	0.723	0.43	LB	170
W3	Kenamu Lake	BS	52.9870°N	59.9483°W	357	1789-2007 (219)	38	0.495	122.2	0.176	0.733	0.51	HBF	215
W3	Kenamu Lake	BF	52.9870°N	59.9483°W	357	1855-2007 (153)	36	0.514	109.8	0.216	0.755	0.4	HBF	215
W4	Lac Betaux	BS	51.9458°N	59.9211°W	332	1803-2007 (205)	31	0.466	125.1	0.184	0.764	0.49	LSF	130
W4	Lac Betaux	BF	51.9458°N	59.9211°W	332	1871-2007 (137)	32	0.433	92.6	0.149	0.65	0.49	LSF	130
C1	Tanya's Tickle	WS	54.8042°N	58.1885°W	4	1852-2007 (156)	38	0.541	97.9	0.258	0.695	0.8	CB	1
C1	Tanya's Tickle	BF	54.8042°N	58.1885°W	4	1789-2007 (219)	35	0.523	67.7	0.212	0.824	0.88	CB	1
C2	Mariana Lake	BS	53.0006°N	58.1401°W	90	1746-2007 (262)	38	0.529	143.2	0.187	0.817	0.42	MB	25
C2	Mariana Lake	BF	53.0006°N	58.1401°W	90	1859-2007 (159)	35	0.514	112.9	0.189	0.788	0.45	MB	25
C3	Freeman's Pond	BS	52.9940°N	57.8402°W	236	1734-2007 (274)	34	0.452	147.4	0.187	0.763	0.4	MB	150
C3	Freeman's Pond	BF	52.9940°N	57.8402°W	236	1840-2007 (168)	30	0.495	110	0.183	0.7	0.5	MB	150
C4	Dumaresq Lake	BS	52.0440°N	57.9904°W	347	1858-2007 (150)	32	0.451	103.5	0.202	0.768	0.42	LST	80
C4	Dumaresq Lake	EL	52.0440°N	57.9904°W	347	1831-2007 (177)	33	0.498	104.1	0.298	0.767	0.65	LST	80
E3	Hawk Bay	BS	51.9805°N	55.9788°W	12	1837-2007 (135)	32	0.478	88.7	0.213	0.807	0.68	CB	0
E3	Hawk Bay	BF	51.9805°N	55.9788°W	12	1892-2007 (116)	33	0.465	81.8	0.209	0.861	0.61	CB	0
E4	Temple Bay	BS	51.9805°N	55.9025°W	20	1918-2007 (90)	33	0.483	61.5	0.214	0.727	0.88	CB	0
E4	Temple Bay	BF	51.9805°N	55.9025°W	20	1906-2007 (102)	33	0.487	56.5	0.198	0.853	1.13	CB	0

Table 2.2 A matrix of Pearson correlation r-values between each radial growth chronology over a 90 year common interval between all chronologies (1918-2006). The cells highlighted in black are significant above the 95% confidence level. The labels indicate the nodal location and species. The first two characters indicate site (see Figure 2.1), while the third character indicates species (F=balsam fir, S=black spruce, L=eastern larch and W=white spruce).

	W1W	W1F	W2S	W2F	W3S	W3F	W4S	W4F	C1W	C1F	C2S	C2F	C3S	C3F	C4S	C4L	E3S	E3F	E4S
W1F	0.49																		
W2S	0.77	0.52																	
W2F	0.49	0.69	0.53																
W3S	0.45	0.59	0.74	0.55															
W3F	0.04	0.58	0.28	0.58	0.69														
W4S	0.40	0.67	0.58	0.56	0.76	0.50													
W4F	0.13	0.48	0.15	0.55	0.22	0.29	0.49												
C1W	0.36	0.38	0.22	0.24	0.40	0.37	0.19	0.11											
C1F	0.31	0.50	0.15	0.41	0.24	0.33	0.31	0.24	0.49										
C2S	0.80	0.58	0.85	0.46	0.66	0.20	0.58	0.20	0.32	0.24									
C2F	0.43	0.59	0.47	0.54	0.46	0.48	0.30	0.32	0.32	0.31	0.53								
C3S	0.63	0.63	0.84	0.58	0.88	0.56	0.77	0.19	0.33	0.27	0.78	0.45							
C3F	0.36	0.66	0.47	0.60	0.68	0.72	0.64	0.42	0.46	0.36	0.49	0.65	0.70						
C4S	0.41	0.31	0.63	0.20	0.70	0.31	0.50	0.02	0.33	0.06	0.58	0.19	0.72	0.43					
C4L	0.39	-0.02	0.26	0.08	0.11	-0.16	0.02	-0.15	-0.01	-0.04	0.32	0.19	0.13	-0.03	0.07				
E3S	0.36	0.40	0.18	0.26	0.28	0.14	0.30	0.33	0.53	0.35	0.45	0.32	0.23	0.30	0.25	0.15			
E3F	0.29	0.12	0.01	0.26	0.11	0.21	-0.07	0.10	0.56	0.44	0.14	0.42	0.06	0.29	0.08	0.25	0.54		
E4S	-0.08	0.23	-0.24	0.02	0.01	0.23	0.16	0.05	0.24	0.23	-0.10	-0.18	0.02	0.16	-0.02	-0.11	0.28	0.05	
E4F	0.02	0.27	-0.13	0.04	0.16	0.31	0.13	0.00	0.48	0.14	-0.07	0.08	0.16	0.34	0.27	0.04	0.24	0.35	0.43

Table 2.3 The number of months that Cartwright's mean monthly temperature illustrated significant correlations to annual radial growth at a 95% significance threshold in a response function analysis performed by program DENDROCLIM2002. The cells highlighted in black have a positive relationship above the 95% confidence threshold. The cells highlighted in grey have a negative correlation above the 95% confidence threshold. The final letter in each chronology label indicates tree species F = balsam fir, S=black spruce, L=eastern larch and W=white spruce.

	W1W	W1F	W2S	W2F	W3S	W3F	W4S	W4F	C1W	C1F	C2S	C2F	C3S	C3F	C4S	C4L	E3S	E3F	E4S	E4F
APR T	-0.10	-0.26	-0.13	-0.09	-0.10	-0.19	-0.12	-0.12	0.02	-0.10	-0.12	-0.16	-0.16	-0.16	-0.15	0.01	-0.11	0.00	-0.10	-0.24
MAY T	0.02	-0.15	-0.03	0.11	0.04	-0.06	-0.02	-0.05	-0.06	-0.08	-0.13	-0.03	-0.02	-0.02	-0.10	0.09	-0.16	0.04	-0.19	-0.20
JUN T	0.07	-0.18	-0.05	0.03	0.04	-0.03	-0.01	-0.19	-0.12	0.08	-0.08	-0.11	-0.01	-0.11	-0.08	0.26	-0.05	0.00	0.05	-0.19
JUL T	0.37	0.21	0.32	0.24	0.34	0.20	0.35	0.10	0.00	0.21	0.34	0.03	0.37	0.19	0.23	0.21	0.22	0.07	0.14	0.04
AUG T	0.01	-0.31	-0.12	-0.12	-0.07	-0.13	-0.19	-0.29	0.00	-0.12	-0.17	-0.15	-0.10	-0.32	-0.05	0.29	-0.09	0.23	-0.05	0.08
SEP T	0.10	-0.20	0.00	0.04	0.04	0.04	-0.19	-0.32	0.22	-0.02	-0.16	-0.15	0.01	-0.15	0.10	0.40	0.06	0.28	0.03	0.20
OCT T	0.10	0.06	-0.04	0.25	0.02	0.17	-0.17	-0.09	0.14	0.19	-0.14	0.16	-0.03	0.06	0.02	0.32	0.15	0.36	-0.01	0.25
NOV T	0.13	0.07	0.09	0.06	0.05	0.01	0.00	-0.17	0.00	0.18	0.00	0.04	0.06	-0.01	-0.07	0.13	0.08	0.03	0.05	0.09
DEC T	-0.08	-0.12	-0.07	0.07	-0.01	0.00	-0.03	-0.16	-0.11	0.21	-0.15	-0.04	-0.04	-0.07	-0.11	0.29	-0.03	0.19	-0.01	-0.08
Jan T	0.16	0.02	0.08	0.15	0.02	-0.09	0.08	-0.07	-0.22	-0.01	0.01	-0.13	0.11	-0.06	0.05	0.04	-0.03	-0.12	0.15	-0.13
Feb T	0.08	-0.01	0.05	0.02	0.02	-0.17	0.09	-0.01	-0.20	0.11	0.03	-0.20	0.09	-0.12	0.04	-0.15	-0.09	-0.13	0.19	-0.13
Mar T	0.04	0.00	-0.06	0.06	-0.05	-0.13	0.03	-0.02	-0.08	0.15	0.04	0.05	-0.02	-0.02	-0.18	-0.02	0.03	0.09	0.05	-0.03
Apr T	-0.10	-0.21	-0.26	-0.08	-0.17	-0.24	-0.10	-0.06	-0.18	-0.02	-0.23	-0.11	-0.22	-0.27	-0.26	0.12	-0.04	0.07	-0.12	-0.16
May T	0.11	0.07	-0.11	0.17	-0.06	-0.03	0.08	0.13	-0.05	0.15	-0.09	0.12	-0.04	0.01	-0.10	0.10	0.04	0.19	0.03	0.03
Jun T	0.26	-0.05	0.01	0.05	0.08	-0.01	0.03	-0.02	0.24	0.16	0.06	0.14	0.05	0.08	0.02	0.34	0.11	0.21	0.18	0.10
Jul T	0.52	0.38	0.39	0.32	0.40	0.26	0.42	0.30	0.31	0.40	0.38	0.22	0.42	0.36	0.26	0.26	0.28	0.24	0.29	0.26
Aug T	0.11	-0.14	-0.06	-0.07	-0.06	-0.03	-0.22	-0.21	0.08	0.04	-0.07	-0.17	-0.09	-0.19	0.06	0.29	0.03	0.18	0.09	0.21
Sep T	0.26	-0.03	-0.02	0.07	0.04	0.06	-0.18	-0.15	0.40	0.18	-0.01	0.02	0.01	-0.01	0.08	0.37	0.15	0.40	0.06	0.33

Table 2.4 The number of months that Cartwright's mean monthly temperature illustrated significant correlations to annual radial growth at a 99% significance threshold in a response function analysis performed by program DENDROCLIM2002. The cells highlighted in black have a positive relationship above the 99% confidence threshold. The cells highlighted in grey have a negative correlation above the 99% confidence threshold.

	W1W	W1F	W2S	W2F	W3S	W3F	W4S	W4F	C1W	C1F	C2S	C2F	C3S	C3F	C4S	C4L	E3S	E3F	E4S	E4F
APR T	-0.10	-0.26	-0.13	-0.09	-0.10	-0.19	-0.12	-0.12	0.02	-0.10	-0.12	-0.16	-0.16	-0.16	-0.15	0.01	-0.11	0.00	-0.10	-0.24
MAY T	0.02	-0.15	-0.03	0.11	0.04	-0.06	-0.02	-0.05	-0.06	-0.08	-0.13	-0.03	-0.02	-0.02	-0.10	0.09	-0.16	0.04	-0.19	-0.20
JUN T	0.07	-0.18	-0.05	0.03	0.04	-0.03	-0.01	-0.19	-0.12	0.08	-0.08	-0.11	-0.01	-0.11	-0.08	0.26	-0.05	0.00	0.05	-0.19
JUL T	0.37	0.21	0.32	0.24	0.34	0.20	0.35	0.10	0.00	0.21	0.34	0.03	0.37	0.19	0.23	0.21	0.22	0.07	0.14	0.04
AUG T	0.01	-0.31	-0.12	-0.12	-0.07	-0.13	-0.19	-0.29	0.00	-0.12	-0.17	-0.15	-0.10	-0.32	-0.05	0.29	-0.09	0.23	-0.05	0.08
SEP T	0.10	-0.20	0.00	0.04	0.04	0.04	-0.19	-0.32	0.22	-0.02	-0.16	-0.15	0.01	-0.15	0.10	0.40	0.06	0.28	0.03	0.20
OCT T	0.10	0.06	-0.04	0.25	0.02	0.17	-0.17	-0.09	0.14	0.19	-0.14	0.16	-0.03	0.06	0.02	0.32	0.15	0.36	-0.01	0.25
NOV T	0.13	0.07	0.09	0.06	0.05	0.01	0.00	-0.17	0.00	0.18	0.00	0.04	0.06	-0.01	-0.07	0.13	0.08	0.03	0.05	0.09
DEC T	-0.08	-0.12	-0.07	0.07	-0.01	0.00	-0.03	-0.16	-0.11	0.21	-0.15	-0.04	-0.04	-0.07	-0.11	0.29	-0.03	0.19	-0.01	-0.08
Jan T	0.16	0.02	0.08	0.15	0.02	-0.09	0.08	-0.07	-0.22	-0.01	0.01	-0.13	0.11	-0.06	0.05	0.04	-0.03	-0.12	0.15	-0.13
Feb T	0.08	-0.01	0.05	0.02	0.02	-0.17	0.09	-0.01	-0.20	0.11	0.03	-0.20	0.09	-0.12	0.04	-0.15	-0.09	-0.13	0.19	-0.13
Mar T	0.04	0.00	-0.06	0.06	-0.05	-0.13	0.03	-0.02	-0.08	0.15	0.04	0.05	-0.02	-0.02	-0.18	-0.02	0.03	0.09	0.05	-0.03
Apr T	-0.10	-0.21	-0.26	-0.08	-0.17	-0.24	-0.10	-0.06	-0.18	-0.02	-0.23	-0.11	-0.22	-0.27	-0.26	0.12	-0.04	0.07	-0.12	-0.16
May T	0.11	0.07	-0.11	0.17	-0.06	-0.03	0.08	0.13	-0.05	0.15	-0.09	0.12	-0.04	0.01	-0.10	0.10	0.04	0.19	0.03	0.03
Jun T	0.26	-0.05	0.01	0.05	0.08	-0.01	0.03	-0.02	0.24	0.16	0.06	0.14	0.05	0.08	0.02	0.34	0.11	0.21	0.18	0.10
Jul T	0.52	0.38	0.39	0.32	0.40	0.26	0.42	0.30	0.31	0.40	0.38	0.22	0.42	0.36	0.26	0.26	0.28	0.24	0.29	0.26
Aug T	0.11	-0.14	-0.06	-0.07	-0.06	-0.03	-0.22	-0.21	0.08	0.04	-0.07	-0.17	-0.09	-0.19	0.06	0.29	0.03	0.18	0.09	0.21
Sep T	0.26	-0.03	-0.02	0.07	0.04	0.06	-0.18	-0.15	0.40	0.18	-0.01	0.02	0.01	-0.01	0.08	0.37	0.15	0.40	0.06	0.33

Figure Captions

Figure 2.1 Labrador with the sample nodes and the associated three north-south columns of sites (W= west C= central and E= east). These placements represent the theoretical placement of sample nodes. The exact nodes were selected within a 5 minute radius of these points (with the exception of C4 which extented the radius to accommodate its location over the Atlantic Ocean).

Figure 2.2 Average mean monthly tempertures in degrees Celcius for the common instrumental record (1942-2007) of the Goose Bay (#71816) and Cartright (#71818) Environment Canada stations. Available from Environment Canada website: http://www.climate.weatheroffice.gc.ca/climateData/canada_e.html

Figure 2.3 Map of Labrador with approximate boundaries of the six zones of radial growth-climate relationships. The 'continental zone' and western part of the 'maritime zone' were defined by Nishimura (2009). The 'arctic maritime zone' and the northern part of the 'subarctic maritime zone' were identified by Kennedy (2011). The extension of the 'maritime zone' eastward, the 'subarctic maritime zone' southward, the delineation of the 'hyper-maritime zone' and the 'upland maritime zone' are from this study.

Figures

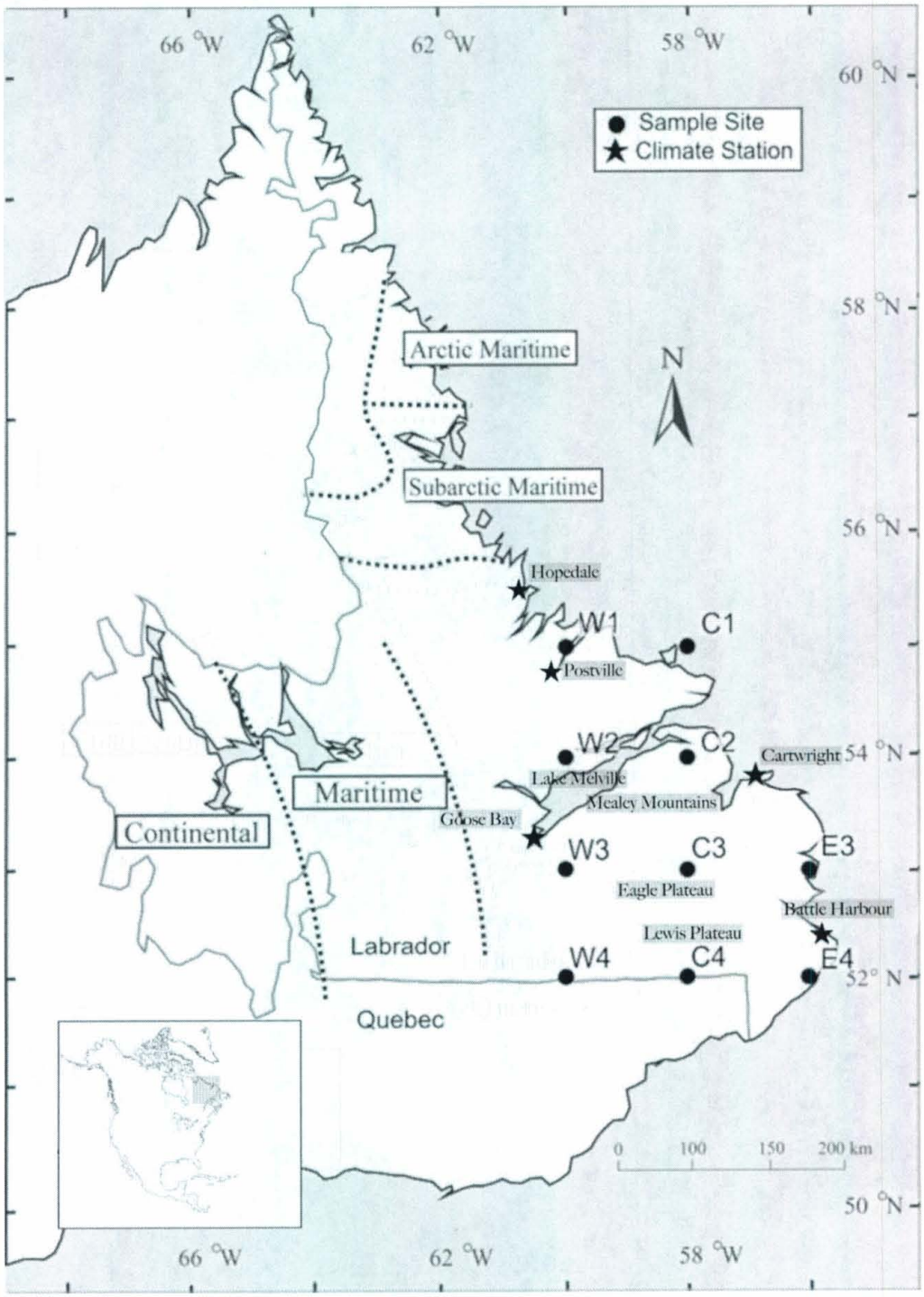

Figure 2.1

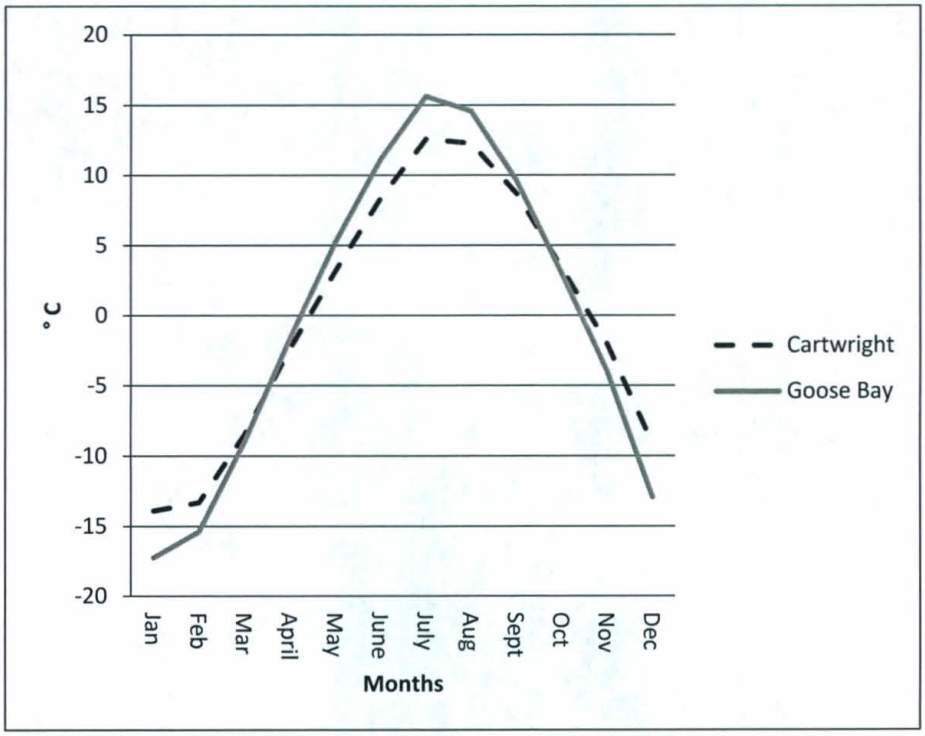
20
15
10
5
0
-5
-10
-15
-20
°C
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec
Months
Cartwright
Goose Bay

Figure 2.2

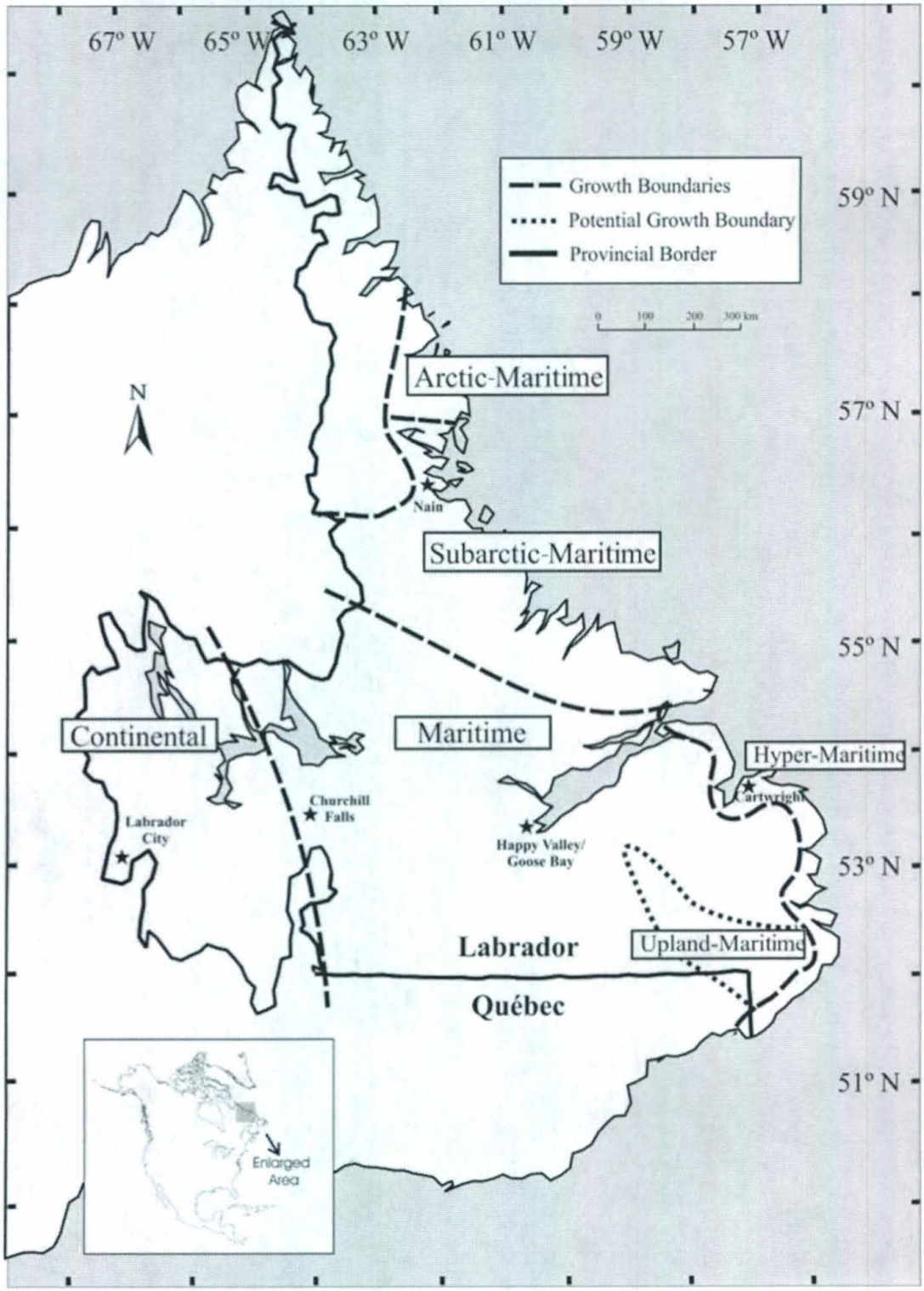
67° W
65° W
63° W
61° W
59° W
57° W
59° N
57° N
55° N
53° N
51° N
Growth Boundaries
Potential Growth Boundary
Provincial Border
0 100 200 300 km
N
Arctic-Maritime
Nain
Subarctic-Maritime
Continental
Maritime
Hyper-Maritime
Cartwright
Churchill Falls
Labrador City
Happy Valley/ Goose Bay
Upland-Maritime
Labrador
Québec
Enlarged Area

Figure 2.3

Co-authorship Statement

The design and development of the research proposal were completed by me, with input from Colin Laroque and Trevor Bell;

The practical aspects of the research were completed by me, with logistical support by Colin Laroque, Trevor Bell, and Mariana Trindade;

All data analysis was completed by myself;

All manuscript preparation was completed by me with comments and editorial suggestions from Colin Laroque and Trevor Bell.

Chapter Three

Tree Ring Evidence of Spruce Budworm Outbreaks Across a Network of Sites in Eastern Labrador

Dean Dumaresq[1], Colin P. Laroque[2] and Trevor Bell[1]

[1]Department of Geography

Memorial University of Newfoundland

St. John's Newfoundland, Canada.

A1B 3X9

[2]Mount Allison Dendrochronology Laboratory

Department of Geography and Environment

Mount Allison University

Sackville, New Brunswick E4L 1A7

Phone (506) 364-2390, Fax (506) 364-2625

E-mail:

ddumaresq@mun.ca

claroque@mta.ca

tbell@mun.ca

3.1. Abstract

Spruce budworm (*Choristoneura fumiferana* (Clem.) (Lepidoptera: Tortricidae)) is a major defoliator of coniferous trees in eastern Canada. Many studies have investigated past disturbance frequencies, intensity, and dispersal of spruce budworm throughout most of this interprovincial region and found several regionally synchronous defoliation events. This study examines past spruce budworm disturbance over a spatially systematic gridded network of ten sites in eastern Labrador, one of the few remaining spatial gaps in this body of research.

Using trembling aspen (*Populous tremuloides* (Michx.)) as a non-host species, balsam fir (*Abies balsamea* (L.) Mill), black spruce (*Picea mariana* (Mill.) B.S.P.) and white spruce (*Picea glauca* (Moench) Voss) radial growth chronologies were analysed using a host/non-host analysis. Events in the 1930s, 1950s and the 1970s were identified as substantial outbreaks periods. The intensity of these outbreaks suggests an eastward migration of the spruce budworm from eastern Quebec, through western Labrador, and into eastern Labrador. At the northern extreme of the study area, a shift in species preference of the spruce budworm from balsam fir to black and white spruce is also observed. A shift in the climate-radial growth relationship in the easternmost sites along the coast restricts the ability to use trembling aspen as a non-host species to delineate spruce budworm defoliation events within this part of the zone.

3.2. Introduction

The effects of spruce budworm (*Choristoneura fumiferana* (Clem.) (Lepidoptera: Tortricidae)) are a natural endemic process in a forest, but can build to have severe effects, particularly those dominated by balsam fir (*Abies balsamea* (L.) Mill.) (Blais 1952) and spruce trees (*Picea* sp.)(Maclean 1980). Budworm larvae emerge in spring and search for suitable feeding sites (Nealis and Régnière 2004) consisting of new bud growth on host species (Volney and Fleming 2007). The defoliation by this feeding can cause more than a 90% decline in radial growth (Ostaff and Maclean1995), and lead to severe tree mortality (Coyea and Margolis 1994). Spruce budworm larvae have been known to feed on a variety of conifer species but have demonstrated a preferred palatability primarily for balsam fir, secondarily white spruce (*Picea glauca* (Moench) Voss), and as a tertiary food source, other species such as black spruce (*Picea mariana* (Mill.) B.S.P.)(Blais 1957, Albert and Jarrett 1981).

The record of past spruce budworm activity in the mixed balsam fir and spruce stands of southeastern Labrador is poorly documented (Figure 3.1), even though there is strong potential for infestation (Nealis and Régnière 2004). Recent studies of neighbouring regions also have revealed several major budworm outbreaks over the past century (Nishimura 2009, Nishimura and Laroque 2010). This paper attempts to fill this gap by reporting the results of a dendroecological study of spruce budworm activity in southeastern Labrador, comparing outbreak chronologies with adjacent regions of western Labrador, Eastern Quebec and Western Newfoundland. In this, it also aims to document the trajectory of budworm dispersal on this region and interprovincial scale.

3.3. Spruce Budworm Outbreaks in Eastern Canada

Eastern Canada has experienced on average, large spruce budworm outbreak cycles on a regional scale every 35 years (Royama et al. 2005), and many factors have been shown to influence the frequency and intensity of these outbreaks. For instance, Greenbank (1956) was the first to identify climate as a major contributing factor to outbreak severity, citing a series of three to four particularly warm and dry summers coincident with severe outbreaks (Otvas and Moody 1978, Hudak 1991). Greenbank (1957) emphasized the effects of dispersal on stand-altering, intense infestations, and later showed that outbreaks were dependent on movement between regions, at times reaching up to an interprovincial scale (Greenbank et al. 1980, Williams and Liebhold 2000). Morris (1963) outlined endemic populations of budworm in eastern Canada as very low to the extent that they could be considered a 'rare' species. During stand-altering epidemic levels, severe defoliation is seen by sharp increases in budworm populations (Greenbank 1963).

Numerous studies have investigated budworm outbreaks in eastern Canada (Figure 3.1). Central and eastern Quebec have been particularly well studied (e.g. Morin 1994, Simard and Payette 2001, Bouchard and Pothier 2010) (Figure 3.1). These studies have found spruce budworm outbreaks dating as far back as 1678 (Boulanger and Arseneault 2004). Quebec has experienced three notable outbreaks in the 20th century. The earliest outbreak occurred between 1910 and 1915 and has been documented in several studies (Bouchard et al. 2006, Bouchard and Pothier 2010). In eastern Quebec, two outbreaks are prevalent in virtually all studies on the subject, the first one in 1950 (e.g., Morin, 1994, Bouchard et al. 2006, Simard et al. 2008; Figure 3.1), although Blais (1983) reported a somewhat similar outbreak on the north shore of the Gulf of St.

Lawrence in 1940. The second major outbreak was slightly less clear. There is inconsistency between studies as some show an outbreak in the 1970s (e.g., Blais 1983, Simard et al. 2008), while others found a slightly later outbreak in 1980 (e.g., Bouchard et al. 2006, Bouchard and Pothier, 2010).

The only study to extensively investigate spruce budworm activity in Labrador was by Nishimura (2009). He identified outbreaks consistent with the timing of those in Quebec. Twentieth century outbreaks in the 1940s, through the 1950s, and in the 1970s coincided with the Quebec data. The 1910 outbreak reported by Bouchard et al. (2006) was not present in Nishimura's (2009) analysis, but there was visual evidence of growth depressions in his tree-ring data.

Atlantic Canada has also been the focus of several studies on spruce budworm (e.g., MacLean 1980, Ostaff and Maclean 1989, Hudak 1991; see also Figure 3.1). Royama (1984) conducted an extensive study of New Brunswick, identifying three major regional outbreaks during the 20th century. The first outbreak commenced in 1912, and was also identified by Greenbank (1956). The second outbreak was dated to 1950 (Greenbank 1956, Royama 1984) and this was followed by a severe outbreak in the mid-1970s which was also identified by Gray and Mackinnon (2007).

Nova Scotia outbreaks were mostly confined to Cape Breton. Neily et al. (2007) identified an outbreak between 1910 and 1915, which was exclusively confined to Cape Breton. Another large outbreak in the early 1950s reached mainland Nova Scotia (Neily et al. 2007), while the largest outbreak occurred in the 1980s (Piene 1989, Ostaff and Maclean 1995, Maclean and Piene 1995). The scale and intensity of this last outbreak surpassed all the previous reports for any location in Nova Scotia.

Newfoundland is one of the few regions without well documented outbreak records for the 20th century (Blais 1983). Studies have identified an outbreak in the mid- to late-1970s (Raske and Alvo 1986, Morini and Harris 2010). An outbreak in 1955 was isolated to the Northern Peninsula (Otvos and Moody 1978).

Moth flights have been recorded by radar over the Cabot Strait traveling with the prevailing winds in a west to east direction (Greenbank et al. 1980). This would indicate a migration route through New Brunswick, and then Cape Breton, to get to Newfoundland. The question remains whether possible outbreaks in eastern Labrador originate from Newfoundland in the south, or instead come from western Labrador.

3.4. Study Area Setting

The study area encompasses a rough triangle in the southeastern portion of Labrador from the Quebec – Labrador border in the south to near Postville in the north and running along the coast to near Henley Harbour along the Strait of Belle Isle (Figure 3.2). The region has a varied topography, climate and ecology.

Eastern Labrador raises from the coastal region to uplands which consist of several topographic features such as the Eagle Plain, the Lewis Plain, running in a north-south direction approximately 100 km west of the southeastern Labrador coast (Foster 1984) and the Mealy Mountains approximately 150 km to the northwest of the Eagle Plain. To the north of the Mealy Mountains, Lake Melville transects the entire study region in an approximate east-west direction. To the north of Lake Melville uplands occur in the west and lowlands occur in the east toward the coast.

Along the coast lower-lying land is subjected to cold onshore climatological circulation patterns (Foster 1984, Roberts et al. 2006). Precipitation along the coast is lower when compared to the uplands farther inland (Roberts et al. 2006).

The majority of the region is dominated by black spruce and balsam fir (Roberts et al. 2006). Other species present in the area include white spruce, eastern larch (*Larix laricina* (Du Roi) K. Koch), trembling aspen (*Populus tremuloides* (Michx.)) and paper birch (*Betula papyrifera* (Marsh.)) (Foster 1984). The interior upland regions are dominated by slow growing forests which are caused by semi-permanently frozen soil and a short growing season (Foster 1984). Soil drainage is the dominant factor that influences soil type and thus vegetation habitat and diversity (Roberts et al.. 2006). The Lewis and Eagle plains, have a thick organic peat soil caused by poor drainage in this region. Black spruce is co-dominant with eastern larch in this zone, rather than with balsam fir (Foster 1984). In the northern part of the region, balsam fir populations declines (Sirois 1999). Tree density of all species begins to wane until treeline conditions are found just north of the study zone (Kennedy 2011). As one moves closer to treeline towards the north, black spruce is slowly replaced by white spruce as the dominant tree species (Kennedy 2011). The coastal zones, to the east of the Eagle and Lewis plateau are mostly barren (Roberts et al. 2006), composed of exposed headlands and protected inlets with conifer trees growing only in low-lying sheltered areas.

The dominant conifer species in eastern Labrador exhibit shifting radial growth to climate relationships on a spatial basis (Dumaresq et al. 2011). Four zones are present within the study area. Central to the region is a 'maritime effect' which is defined by a

dominate radial growth response to July temperatures (Dumaresq et al. 2011). To the east, along the coast, a 'hyper maritime effect' shares the July temperature response but is also delineated by an extended growing season into September. On the Lewis Plain an 'upland maritime effect' is less explored but appears to have similar radial growth to the expressed climate patterns of the hyper maritime zone, yet it does not share the same proximity to the coast (Dumaresq et al. 2011). In this zone, the common co-dominate species are black spruce and eastern larch rather than black spruce and balsam fir. To the north of the study area the 'subarctic maritime zone' is characterized by a growth response to July temperature and also illustrates a switch in dominance from black to white spruce. White spruce in this zone exhibits an earlier commencement to the growing season (Dumaresq et al. 2011). This species dominance and the growing season shift can be seen on a large scale extending inland and northerly extending beyond the range of this study (Kennedy 2011).

3.5. Sampling Approach and Methods

A gridded sampling approach was employed to facilitate a systematic spatial analysis of the study region. Each site was selected at the closest accessible point at the intersection of 52, 53, 54, and 55 degrees north latitude and 56, 58, and 60 degrees west longitude where these intersections occurred over or within 10 kilometers of land (Figure 3.2, Table 3.1). This sampling method was selected in order to create a homogeneous grid across eastern Labrador that connects to Nishimura's (2009) spruce budworm investigations and Nishimura and Laroque's (2011) larch sawfly study. As a whole this sampling method completes a continuous, homogeneous sampling grid that extends over virtually all of

Labrador's contiguous boreal forest. In total, 10 study nodes were sampled. Accessible points were defined as locations of mature mixed conifer stands within five minutes latitude of the intersection point (c.f., Nishimura 2009). A suitable sampling stand consisted of two co-dominant tree species and the absence of fire disturbance (c.f., Nishimura 2009).

Each node was labelled according to their position in the grid: western, central and eastern nodes were designated W, C and E, respectively. The nodes were further labelled numerically one to four, from north to south, except along the eastern grid line where only two coastal nodes occur in the southeast (Figure 3.2). Species were also signified with a letter designation, balsam fir, black spruce and white spruce were assigned F, S, and WS respectively.

At each node, the two species whose foliage was known to be most palatable to spruce budworm were selected if available (i.e., balsam fir, white spruce, and black spruce, respectively). The target species at most nodes were black spruce and balsam fir, except at nodes W1, C1 and C4. At W1 and C1 white spruce, generally the rarest host tree species within the entire study grid was found in sufficient quantity to make a chronology. At C4 the only species that was susceptible to spruce budworm was black spruce.

Two increment cores were extracted at breast height from 20 mature trees from each species, at each node, for a total of 40 cores per species, 80 cores per node, where two species were sampled. The cores were processed and tree rings measured, crossdated,

and standardized according to standard protocols (see Dumaresq et al. (2012) for further description). Both a master chronology for each species at each node, and a master regional chronology (average of all nodal chronologies) were generated for subsequent analyses.

3.6. Analytical Methods

To discern outbreaks of spruce budworm, radial growth depressions with a classic radial-growth defoliation signature (an 8-12 year reduction of growth, followed by an 8-12 year restabilization of growth) were identified in each tree-ring chronology at each node. This approach followed the host/non-host analysis protocol of Swetnam et al. (1995) and employed both visual and statistical methods. Trembling aspen was used as the non-host species. Nealis and Régenière (2004) characterized aspen to typically experience an increase in radial growth during budworm outbreaks. They attributed this to a reduction in competition for resources from tree species affected by the spruce budworm. Local aspen chronologies from Goose Bay, Cartwright and Port Hope Simpson generated by Kershaw and Laroque (2011) were available for the non-host record in this study. To test whether all species were responding to similar external growth influences and to select the most appropriate non-host standardized chronology for the study, Pearson product moment analyses were carried out between i) the regional standardized chronologies for aspen, balsam fir, black spruce and white spruce and ii) each of the three aspen standardized chronologies and individual species at each node, respectively.

Using non-host species with similar radial-growth trends to the host species is necessary as it provides an indication that the radial growth patterns were influenced by similar overall environmental conditions (Speers, 2010). This is the basis for the host/non-host analysis as it relies on identifying radial-growth depressions in the host species relative to that of the non-host, specifically during the times of infestation. By using species with similar relationships to environmental parameters such as climate, it then eliminates climate as a possible mechanism for changes in the radial-growth rates.

In the visual analysis, graphed radial-growth trends of host and non-host species were compared. Periods were identified when the growth of a host species was reduced below that of the non-host species, resulting in a decoupling of the radial-growth trends. The statistical analysis was performed using the computer program *OUTBREAK* (version 1.50P; Swetnam et al. 1995, Holmes and Swetnam 1996, Speer et al. 2001). The program identifies reduced radial-growth patterns specific to spruce budworm by adopting specific growth depression thresholds and radial growth recovery periods. For this study an individual tree was considered to be experiencing significantly reduced radial growth when the period of growth reduction spanned a minimum of 8 years where at least one of these year's radial grow was less than the threshold standard deviations of the non-host (Swetnam et al. 1995). This standard deviation threshold was calculated based on radial growth of the host trees in Labrador. In addition, an individual node was considered to be experiencing an outbreak when for two or more consecutive years 50% or more of the individual cores at a node were experiencing a significant radial growth reduction, as defined above.

3.7. Results

Regional chronologies for the three host species had a similar growth trend to the regional trembling aspen chronology based on the two-tailed Pearson correlation test (Table 3.2). For individual aspen tree ring chronologies, the Cartwright chronology displayed the strongest correlations with most (16 of 19) individual species chronologies by grid node (Table 3.3). The other two aspen chronologies available to this study – Goose Bay and Port Hope Simpson – had fewer significant correlations (15 of 38) with the host species and thus the Cartwright aspen chronology was adopted as the most suitable non-host chronology available for the study.

At the nodal level, all of the western and central host chronologies, with one exception, correlated with the Cartwright aspen tree ring chronology at the 99% confidence level. The exception C4S had a significant correlation at the 95% level. Of the eastern nodes, the only chronology with a significant correlation with Cartwright aspen was the balsam fir chronology at E3, the more northerly of the two eastern nodes.

Visual analyses of plotted host/non-host chronologies at each node illustrated the strong similarity in growing trends with some clear departures. In particular the strongest similarities in growth trends occur between aspen and spruce (both black and white), although balsam fir also shows strong overlap (Figure 3.4a, 3.4b). The eastern nodes displayed the greatest decoupling with aspen of any of the chronologies, particularly in the earlier and later portions of each chronology, which supports the results of the correlation analysis (Table 3.3).

3.7.1. *Outbreak chronologies and patterns*

The three threshold limits calculated for the OUTBREAK values that were used, were all found to be within a similar range to Nishimura and Laroque (2011) (black spruce =1.19 standard deviations from the mean ring-width index; balsam fir = 1.23 standard deviations; white spruce 1.33 standard deviations). These values are comparable to the only other calculated threshold values that were previously used in Labrador (Nishimura 2009, Nishimura and Laroque 2011).

Evidence of periodic spruce budworm outbreaks is apparent in the results from the *OUTBREAK* analysis (Figure 3.5a and 3.5b). During the 100-year window of this study, three regional outbreaks are consistently apparent across the black and white spruce (Figure 3.5a) and balsam fir chronologies (Figure 3.5b). These major outbreaks, defined by peaks in the number of trees infested by spruce budworm at the majority of nodes across the study area, occurred approximately in 1932, 1950, and 1973. These years are defined as the modal year of peak outbreaks across all sites.

During the early 1930s, 14 of the 19 chronologies experienced an outbreak. The year 1932 was the modal peak across the affected chronologies, although peak years ranged across the grid from 1927 to 1938. The sample depth in several chronologies is low during this outbreak (C1S, E4S, E4F). This is likely due to their proximity to the coast (exposure to harsh conditions) and that they are younger trees. The onset of this outbreak is fairly abrupt, with little to no budworm evidence prior to the late 1920s and

early 1930s. This is partly due to a reduction in sample depth toward the beginning of the chronologies.

All eight western chronologies, whether spruce or fir, recorded a strong infestation during this period, with at least 50% of the samples in each chronology affected (Table 3.4). The central and the eastern chronologies displayed more mixed results with nodes C1F, C2S, C4S and the fir chronologies in the east, experiencing less than 50% affected, and nodes C1S, C2F, C3F, and C3S and the spruce chronologies in the east exhibitiong more than 50% of the samples showing signs of infestation. Overall, the pattern suggests a stronger outbreak intensity to the northwest of the study region (Table 3.4).

Between 1932 and 1942 there is a decline in the relative frequency of trees experiencing infestation at all nodes (Table 3.4). Most nodes drop below the 50% infestation level during this period. Thirteen of the 16 nodes (80%) record their lowest infestation level in 1942, while nodes C4S, E3F and W3F have their lowest levels in 1939, 1940 and 1948, respectively. The only node that recorded zero infested trees during the recovery interval was C1F; the remainder (12.5%) had between 24 and 65 percent of the trees infested. Following infestation recovery, all nodes show a gradual increase again in infestation levels with the onset of the 1950 outbreak (Table 3.4).

The 1950 outbreak was present at all sites (Table 3.4). Of the eight western chronologies five recorded 80% or higher infestation rates. Nodes W2F and W3F had percentages in the high 70s, while node W3S only had 53% of its cores displaying signs of infestation. The chronologies of the central nodes all recorded early infestation peaks

in the mid- to late-1940s (Table 3.4). At node C2S both the spruce and fir chronologies record their peak outbreak in 1944. The peak of infestation in the spruce chronology spanned 7 years until 1951, while the fir peak lasted only 2 years until 1946. Farther south, C3S and C4S infestations both peaked in 1949 with between 50% and 60% of their samples affected (Table 4). Fir at node C3 peaked at 73% infested trees by 1951. The most northerly (C1) node peaked in 1950 with half of both the spruce and fir samples infested. All eastern nodes peaked early in the 1950s. Most chronologies (3 of 4) in the east exhibited over 50% infestation with the exception of E4F which peaked at 39% in 1952. The 1950 outbreak shows a fairly uniform impact across the sampling grid with no consistent pattern in its spatial onset (Table 3.4).

The year 1959 marked an abrupt decline in the number of infested trees at each node (Table 3.4). From 1960 to 1965 all nodes experience little to no sign of infestation and then between 1965 and 1975 there is an abrupt rise in the percentage of infested trees. Of the 18 chronologies in the study, eight record more than 50% of their samples infested during the early 1970s, including all four northern spruce (W1S, C1S, W2S, C2S) and W3S chronologies. Only fir chronologies at W2 and C2 nodes have greater than 50% infested samples (Table 3.4). The remainder of the chronologies during this outbreak have less than 50% infested samples (Table 3.4). The 1980s experienced a gradual decline seen in Table 3.4, although not shown in this Table, the decline continues into the 1990s in all chronologies.

3.8. Discussion

3.8.1. Host/non-host radial growth relationships

The visual and statistical comparisons of each host chronology to the non-host aspen chronology, revealed several regionally synchronous events with the exception of the easternmost nodes (E3, E4). These nodes illustrated different growth trends compared with the central and western sites (Figure 3.3, Table 3.2). Radial growth in these two eastern nodes respond to hyper-maritime climate controls (Dumaresq et al. 2011) in contrast to the maritime influence on radial growth that have a significant control on the radial growth of aspen (Kershaw and Laroque, 2011). As a result there is a fundamental disparity in climate drivers and radial growth responses between the host/non-host tree-ring chronologies in these eastern sites. For this reason, the hyper-maritime nodes are excluded from further discussion of spruce budworm outbreaks in the sampling grid, because any results would be at best, inconclusive.

Radial growth in the two northernmost nodes in the sampling grid (W1, C1) responds to a sub-arctic maritime climate effect, first described by Kennedy (2011) and identified in southeastern Labrador by Dumaresq et al. (2012). Despite this variation in radial growth-climate response, the host tree ring chronologies from these nodes closely follow similar trends to the non-host aspen chronology (Figure 3.4a and 3.4b, Table 3.3) and consequently are included in the regional analysis of spruce budworm outbreaks.

3.8.2. Spruce Budworm Outbreaks

Of the three spruce budworm outbreaks recorded in southeastern Labrador, the 1950s outbreak was the most intense. This outbreak matches the timing of a mass outbreak farther west in Labrador and Quebec (e.g. Nishimura 2009, Blais 1952, Krause and Morin 1999) (Figure 3.1). The rapid onset, intensity, and prolific nature of the 1950s outbreak made it difficult to identify a spatial pattern in the directionality of the infestation for the outbreak and thus no dispersal source can readily be identified in this study. This infestation is consistent with above-average summer and winter temperatures experienced throughout Newfoundland and Labrador (Banfield and Jacobs 1998). One explanation for this may be related to the fact that the earlier outbreak did not completely dissipate in the 1940s and consequently the outbreak was caused by a recovery of a population already well represented in the forests within the study region, rather than one that migrated in from an adjacent region. The sharp decline in the infestation rate seen at the end of the 1950s is likely due to a very sharp cooling in the winter of 1959 (Banfield and Jacobs 1998). It is our belief that in the 1950s infestation instance, climate was the driving factor that brought a native population up to epidemic levels (Greenbank 1956), rather than a dispersal following prevailing winds from western regions experiencing epidemic outbreaks (Greenbank 1957).

The less intense 1930s and 1970s spruce budworm outbreaks provided a clearer sense of dispersal patterns into southeastern Labrador. In contrast to the 1950s outbreak, the infestation intensity at all nodes was virtually zero prior to both the 1930s and 1970s outbreaks. This strongly suggests a non-local source for both outbreaks. The pattern of

infestation intensity and the timing of outbreaks across the sampling grid suggest a stronger and earlier presence in western nodes compared to central nodes. For example, all species in the western nodes fully experienced the 1930s outbreak, in contrast to species in the central nodes which experienced a more scattered presence in extent and intensity. In the case of the 1970s outbreak, the infestation was more concentrated in the northwestern corner of the grid and in black and white spruce trees (Table 3.4). For both outbreaks, a dispersal path from western Labrador appears most likely with a gradual eastward fade towards the Labrador coast. Although the 1970s outbreak was clearly identified in western Labrador by Nishimura (2009) and eastern Quebec by Simard et al. (2008), a similar source and correlative outbreak to the west is not obvious for the 1930s outbreak (Figure 3.1).

The 1970s outbreak exhibited a north-to-south gradient in infestation intensity and dispersal where white spruce experienced the outbreak farther to the north than the balsam fir chronologies. This northern influence on the spruce budworm outbreak may be related to ecological tolerances as balsam fir distribution is less contiguous towards the northern part of the grid. Although the density of fir becomes less contiguous in the north from the coast westward across the study site, this does not necessary reflect the overall density of the forest as white spruce starts to become more dominant in northern regions of Labrador (Kennedy 2011). It is also possible that the pattern reflects the timing of budburst and that this phenological factor plays a key role in the choice of target host for the budworm. The emergence of budworm larvae has been strongly linked not only to climate factors (i.e. degree days) but also to the synchronicity with pheonlogical cycles of

its host tree species (Volney and Cerezke 1991). With limited fir populations and a shortened growing season near balsam fir's northern limit at 45°N (Roberts et al. 2006), it is possible that budworm are responding more closely to the bud burst of the more climate tolerant white spruce, than to the balsam fir.

3.9. Conclusion

One of the main goals of this paper was to better understand if spruce budworm infestations acted in a synchronous manner throughout eastern Labrador. Evidence from the 20th century suggests that they do, as broadly-based regional synchronous infestations occurred in most of eastern Labrador in the 1930s, 1950s and 1970s. The exception to this broad trend may occur in the extreme-eastern coastal areas where reliable results could not be gleaned from this study. This was due to a decoupling of the radial growth patterns between the spruce budworm host species (black spruce and balsam fir) and non-host species (aspen) caused to a transition in the forest-climate relationship from the more common maritime zone, to the altered climates of the hyper-maritime zone (Dumaresq et al. 2011). Underlying this push of infestations up to the boundaries of the transition zone, is the evidence that most of the major budworm events are derived from the eastward expansion of budworm from eastern Quebec and western Labrador. Little to no evidence indicates that outbreak events in the hyper-maritime climate zone are moving up the coast from Newfoundland. Although a few decoupling events are present within the limited coastal data points within this study, any speculation is baseless. Without suitable non-host chronologies and a change in the relatively short host chronologies in the southeast portion of the study site, the hyper-maritime zone will continue to require further

sampling and analysis to try to understand the past disturbance regime from spruce budworm activities.

Overlying all of these findings is the importance of climatic conditions within the growing environment of the forests in eastern Labrador. Climatic conditions help define where the trees are growing on the landscape in an east-west and north-south fashion (Dumaresq et al. 2011, Kennedy 2011, Nishimura and Laroque 2011), and climatic conditions also define the locations where major infestations of spruce budworm build and disperse from adjacent regions (Greenbank 1957, Greenbank 1980). It will be the nature and location of these shifting boundaries of the climates of eastern Labrador in the face of rapid climate change that will ultimately define the ability of spruce budworm occurrences in eastern Labrador to expand or contract.

Rapid spring warming of up to two to three °C by 2050 is predicted for Labrador (Trenberth, et al. 2007, Bell et al. 2008), but the timing and location of such warming, in concert with the changing bioclimatic interactions along the boundaries of the subarctic maritime/maritime/hyper-maritime forest zones may very well define future spruce budworm effects in the forests of eastern Labrador. If the boundaries continue to be present because of strongly positioned climate forcers such as the effects from the Labrador Sea, then a continuation of budworm cycles similar in frequency and magnitude to the 20th century are probable. MacCarthy and Weetman (2006) and MacCarthy (2001) found the isolation and humid climate of coastal Newfoundland and Labrador forests to have longer stand and forest scale disturbance cycles, ranging up to 500 years (Foster 1983). If the rapidly warming climates change the location, and more interestingly, the

timing of specific ecological processes that are deemed to be key within the ecology of the forests and or budworm life cycles (e.g., bud burst), then the frequency and magnitude of future outbreaks in eastern Labrador will likely be altered. With Labrador climate scenarios predicting increased spring temperatures (Bell et al. 2008), the possibility of increased budworm frequency and intensity is possible. Coupled with predictions of 10%-20% increase in rain events (Bell et al. 2008) and the proximity to the Labrador Sea, there is also a possibility of reduced budworm events. Overall with the uncertainty in changing climates and precisely how budworm will react to such changes emphasize the need for continued study and monitoring both climatically and ecologically.

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Table 3.1 - The site details of each location and statistics relating the each crossdated master chronology. BS=black spruce; WS=white spruce; EL= eastern larch; BF = balsam fir; TA = Trembling Aspen; MSI = mean series intercorrelation (calculated on 50-year lagged segments); MTA = mean tree age; AMS = average mean sensitivity; AC=unfiltered auto-correlation; MM = mean measurement (annual increment); HST = high subarctic tundra; LB = low boreal; HBF =high boreal forest; LSF = low subarctic forest; CB = costal barrens; MB = mid-boreal forest; NA = not available

Site	Site Name	Species	Latitude	Longitude	Elevation (m asl)	Length of Chronology	No. of Cores	MSI	MTA	AMS	AC	MM
W1	W1S	WS	54.8141°N	59.9345°W	28	1666-2007 (342)	36	0.534	156	0.198	0.803	0.43
W1	W1F	BF	54.8141°N	59.9345°W	28	1807-2007 (201)	33	0.504	113.8	0.195	0.788	0.43
W2	W2S	BS	53.8849°N	60.0025°W	283	1751-2007 (257)	34	0.525	199.6	0.189	0.82	0.41
W2	W2F	BF	53.8849°N	60.0025°W	283	1845-2007 (163)	34	0.47	117.3	0.205	0.723	0.43
W3	W3S	BS	52.9870°N	59.9483°W	357	1789-2007 (219)	38	0.495	122.2	0.176	0.733	0.51
W3	W3F	BF	52.9870°N	59.9483°W	357	1855-2007 (153)	36	0.514	109.8	0.216	0.755	0.4
W4	W4S	BS	51.9458°N	59.9211°W	332	1803-2007 (205)	31	0.466	125.1	0.184	0.764	0.49
W4	W4F	BF	51.9458°N	59.9211°W	332	1871-2007 (137)	32	0.433	92.6	0.149	0.65	0.49
C1	C1WS	WS	54.8042°N	58.1885°W	4	1852-2007 (156)	38	0.541	97.9	0.258	0.695	0.8
C1	C1F	BF	54.8042°N	58.1885°W	4	1789-2007 (219)	35	0.523	67.7	0.212	0.824	0.88
C2	C2S	BS	53.0006°N	58.1401°W	90	1746-2007 (262)	38	0.529	143.2	0.187	0.817	0.42
C2	C2F	BF	53.0006°N	58.1401°W	90	1859-2007 (159)	35	0.514	112.9	0.189	0.788	0.45
C3	C3S	BS	52.9940°N	57.8402°W	236	1734-2007 (274)	34	0.452	147.4	0.187	0.763	0.4
C3	C3F	BF	52.9940°N	57.8402°W	236	1840-2007 (168)	30	0.495	110	0.183	0.7	0.5
C4	C4S	BS	52.0440°N	57.9904°W	347	1858-2007 (150)	32	0.451	103.5	0.202	0.768	0.42
E3	E3S	BS	52.9940°N	55.9890°W	12	1837-2007 (135)	32	0.478	88.7	0.213	0.807	0.68
E3	E3F	BF	52.9940°N	55.9890°W	12	1892-2007 (116)	33	0.465	81.8	0.209	0.861	0.61
E4	E4S	BS	51.9805°N	55.9025°W	20	1918-2007 (90)	33	0.483	61.5	0.214	0.727	0.88
E4	E4F	BF	51.9805°N	55.9025°W	20	1906-2007 (102)	33	0.487	56.5	0.198	0.853	1.13
CARTWRIGHT ASPEN		TA	53.4692°N	57.1393°W	NA	1865-2007 (143)	40	0.499	NA	0.325	0.785	NA
GOOSE BAY ASPEN		TA	53.2882°N	60.4094°W	NA	1956-2007 (52)	40	0.527	NA	0.239	0.777	NA
PORT HOPE ASPEN		TA	52.7202°N	56.6923°W	NA	1890 -2007 (118)	40	0.551	NA	0.251	0.789	NA

Table 3.2 Pearson product moment correlation r-values between the regional trembling aspen chronolongy and the regional balsam fir, black spruce, and white spruce chronologies.

	r-value	p-value
Balsam Fir	0.3465	0.000023
Black Spruce	0.3445	0.000002
White Spruce	0.3197	0.000099

Table 3.3 Pearson product moment correlation r-values between individual species at each node and trembling aspen chronologies. Dark shaded cells represent those values that surpass the 99% confidence threshold. The light shaded cell surpassed the 95% confidence threshhold. n equals to the common interval between given pairs of chronologies (see Table 3.1 for values).

Site	Cartwright aspen	Port Hope aspen	Goose Bay aspen
W1F	0.388	0.223	0.423
W1S	0.402	0.199	0.334
W2F	0.415	0.212	0.296
W2S	0.371	0.124	0.177
W3F	0.313	-0.011	0.046
WFS	0.484	0.243	0.103
W4F	0.242	-0.120	0.182
W4S	0.365	0.087	0.307
C1F	0.341	0.206	0.569
C1S	0.286	0.321	0.229
C2F	0.380	0.113	0.269
C2S	0.396	0.222	0.247
C3F	0.484	0.015	0.242
C3S	0.481	0.115	0.197
C4S	0.188	0.165	0.017
E3F	0.327	0.089	0.225
E3S	0.096	0.205	0.256
E4F	0.182	0.052	0.285
E4S	0.017	0.019	0.371

Table 3.4 Percentage of sampled trees exhibiting signs of infestation at each node. Data is displayed on an annual resolution. Grey cells indicate infestations greater than 50%. Black cells indicate infestations over 75%. The upper Table displays data of black spruce and white spruce. The lower Table displays balsam fir data.

Year	1925-1929					1930-1939										1940-1941												1950-1959												1960-1969												1970-1979												1980-1985						
W1F	35	65	67	68	71	75	72	72	67	70	68	61	61	58	58	58	45	29	32	48	58	58	71	77	81	84	84	78	76	76	70	67	67	58	52	0	0	0	0	0	9	15	15	15	15	33	36	42	42	42	42	39	30	30	30	27	27	21	21	18	18
W2F	43	50	53	52	55	55	55	53	52	52	67	61	61	64	58	55	48	48	55	70	79	76	71	71	76	79	76	76	76	76	71	71	68	68	59	3	3	0	0	3	15	32	44	47	47	59	59	59	59	59	59	53	29	29	26	26	26	24	24	24	21
W3F	82	85	88	88	88	88	88	88	82	85	88	85	85	82	82	82	82	71	71	68	69	60	57	51	56	78	72	64	64	64	64	64	64	64	61	0	0	0	0	6	6	31	34	40	46	49	49	49	49	49	49	38	12	12	12	12	12	9	9	9	9
W4F	38	43	43	40	52	52	52	56	46	42	52	48	52	52	52	50	43	37	47	60	73	71	74	77	77	91	88	81	84	84	78	72	72	72	66	13	9	9	3	16	22	31	38	38	41	41	41	41	41	41	38	22	6	3	3	3	3	3	3	3	3
C1F	0	20	20	30	30	30	27	[illegible]	[illegible]	27	18	15	13	13	13	12	0	0	11	30	32	29	33	44	48	52	50	48	48	48	46	46	46	46	46	4	0	0	0	0	0	42	42	42	42	48	48	48	48	48	48	44	16	13	25	25	28	28	28	28	44
C2F	36	45	45	48	55	58	58	[illegible]	[illegible]	58	72	72	72	69	66	66	69	66	69	78	78	78	75	72	72	75	76	76	74	71	71	71	71	69	66	0	0	3	3	3	34	54	60	60	60	60	60	60	60	60	60	51	23	26	31	31	31	31	34	34	34
C3F	36	43	45	55	72	76	76	79	79	79	79	76	83	83	67	63	60	50	60	63	67	63	67	57	53	70	73	70	70	67	67	63	60	57	53	7	3	0	0	0	7	17	20	20	20	23	23	23	23	23	23	17	13	13	17	17	17	13	13	13	13
E3F	5	10	14	19	24	24	23	23	22	22	30	24	28	27	23	21	25	27	30	37	53	57	57	73	73	79	79	76	76	76	73	64	58	58	58	3	3	6	3	3	9	73	79	79	79	85	84	84	84	84	84	78	41	41	44	44	45	45	42	42	42
E4F	0	0	25	25	25	17	14	13	10	10	10	9	9	8	8	8	0	0	0	0	7	7	6	19	24	35	39	39	39	39	39	39	33	29	29	0	0	0	0	0	4	12	16	16	16	31	31	37	37	36	36	38	32	32	39	38	38	34	31	31	31

Year	1925-1929					1930-1939										1940-1941												1950-1959												1960-1969												1970-1979												1980-1985						
W1S	6	12	32	44	63	63	63	63	63	63	66	63	69	63	60	63	60	57	60	83	86	86	94	94	94	94	94	94	94	94	83	83	75	69	0	0	0	0	0	17	67	69	69	72	86	89	89	89	89	88	85	68	65	65	68	68	68	68	68	65
W2S	15	35	47	50	62	62	62	62	59	65	76	71	74	74	74	74	65	65	74	76	76	76	76	85	88	88	88	82	82	82	82	79	79	79	74	9	9	3	0	6	29	47	59	59	62	74	74	74	74	74	74	74	59	59	64	64	64	58	58	58	58
W3S	27	49	59	62	68	68	68	68	65	62	58	42	45	45	34	32	32	24	39	39	37	37	39	45	47	53	50	45	45	47	47	47	47	47	42	5	5	3	0	0	5	18	24	24	37	58	58	58	58	58	58	58	32	32	32	30	30	22	24	24	24
W4S	33	50	52	61	68	68	68	68	68	65	68	65	65	65	58	58	45	45	71	74	74	74	77	71	81	81	81	71	71	71	71	65	65	65	50	0	0	3	3	3	3	13	20	20	23	30	30	30	30	30	30	27	30	30	30	23	23	20	20	20	20
C1S	30	43	43	55	55	55	55	52	46	44	41	37	36	31	29	26	19	15	24	23	40	40	49	50	50	51	49	43	43	45	45	45	45	42	39	5	5	5	0	3	13	37	45	45	45	61	63	63	63	63	63	58	45	39	37	37	37	34	34	34	32
C2S	11	18	29	39	42	47	47	47	47	45	47	47	53	53	47	45	42	42	71	74	74	74	68	74	74	74	74	71	71	71	68	66	66	66	66	3	3	3	3	3	5	42	45	45	45	55	55	55	55	55	55	55	39	39	39	39	39	37	37	37	37
C3S	28	44	56	59	63	63	63	66	66	66	66	59	59	59	47	47	44	38	50	50	56	56	50	53	59	58	58	55	55	55	48	48	45	39	33	6	3	3	0	0	0	21	27	27	27	36	38	38	38	38	38	34	31	28	28	28	29	29	30	30	30
C4S	18	36	43	42	46	44	44	44	44	48	46	39	39	38	31	34	24	41	38	45	45	43	40	47	53	53	53	53	53	53	50	50	50	47	38	0	0	0	0	0	3	19	25	25	25	34	34	34	34	31	31	31	31	31	31	31	31	31	31	31	31
E3S	21	35	40	45	42	40	40	40	44	44	56	56	56	54	48	48	50	36	40	45	48	53	56	56	63	63	59	[illegible]	59	63	56	47	47	47	47	3	3	3	3	6	9	38	38	38	38	44	47	47	47	47	47	44	41	38	38	34	34	19	19	19	19
E4S	100	100	100	100	100	67	67	67	50	40	40	40	60	50	50	56	50	50	62	67	67	59	65	63	60	57	50	42	40	37	37	31	28	20	20	0	0	0	3	6	6	13	16	16	19	44	44	44	44	44	42	42	27	18	18	18	18	18	15	15	18

Figure Captions

Figure 3.1 Chart comparing results from past spruce budworm studies in eastern Canada. The black dots indicate outbreaks identified by a specific year. The elongated black bars indicate outbreaks identified over a multi-years timespan.

Figure 3.2 Labrador with the sample nodes and the associated three north-south columns of sites (W= west C= central and E= east). These placements represent the theoretical placement of sample nodes. The exact nodes were selected within a 5 minute radius of these points (with the exception of C4 which extented the radius to accommodate its location over the Atlantic Ocean). Aspen chronologies are denoted, dispersed throughout the center of the study area.

Figure 3.3 Standardized regional radial-growth chronologies for black spruce, balsam fir, white spruce and trembling aspen. Visually it is apparent that radial growth of all four chronologies exhibit similar long term trends.

Figure 3.4a Balsam fir (host) nodal chronologies graphed with Cartwright aspen (non-host) standardized chronology. Graphs are arranged according to the gridded sampling format based on their relative geographic position (Figure 3.2)

Figure 3.4b Black spruce (host) nodal chronologies graphed with Cartwright aspen (non-host) standardized chronology. Graphs are arranged according to the gridded sampling format based on their relative geographic position (Figure 3.2)

Figure 3.5a Percentage of sampled black spruce trees infected by budworm over time at each site complete and sample depth of each given chronology

Figure 3.5b Percentage of sampled balsam trees infected by budworm over time at each site and sample depth of each given chronology.

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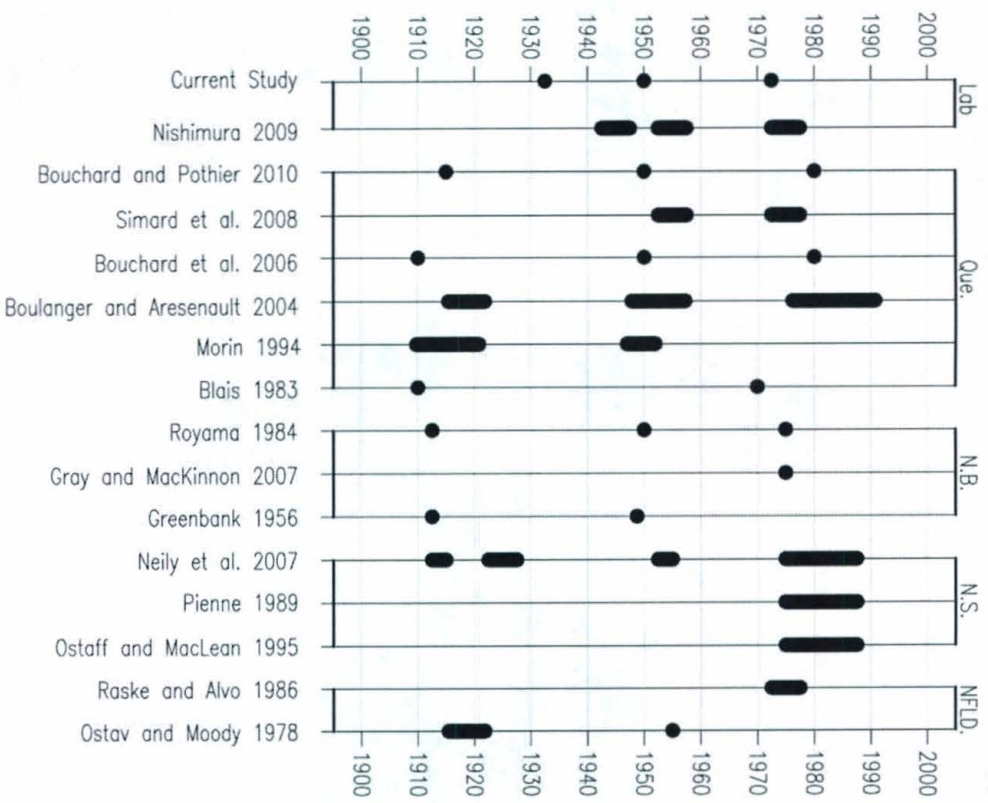

1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Current Study
Nishimura 2009
Bouchard and Pothier 2010
Simard et al. 2008
Bouchard et al. 2006
Boulanger and Aresenault 2004
Morin 1994
Blais 1983
Royama 1984
Gray and MacKinnon 2007
Greenbank 1956
Neily et al. 2007
Pienne 1989
Ostaff and MacLean 1995
Raske and Alvo 1986
Ostav and Moody 1978
Lab
Que.
N.B.
N.S.
NFLD.

Figure 3.1

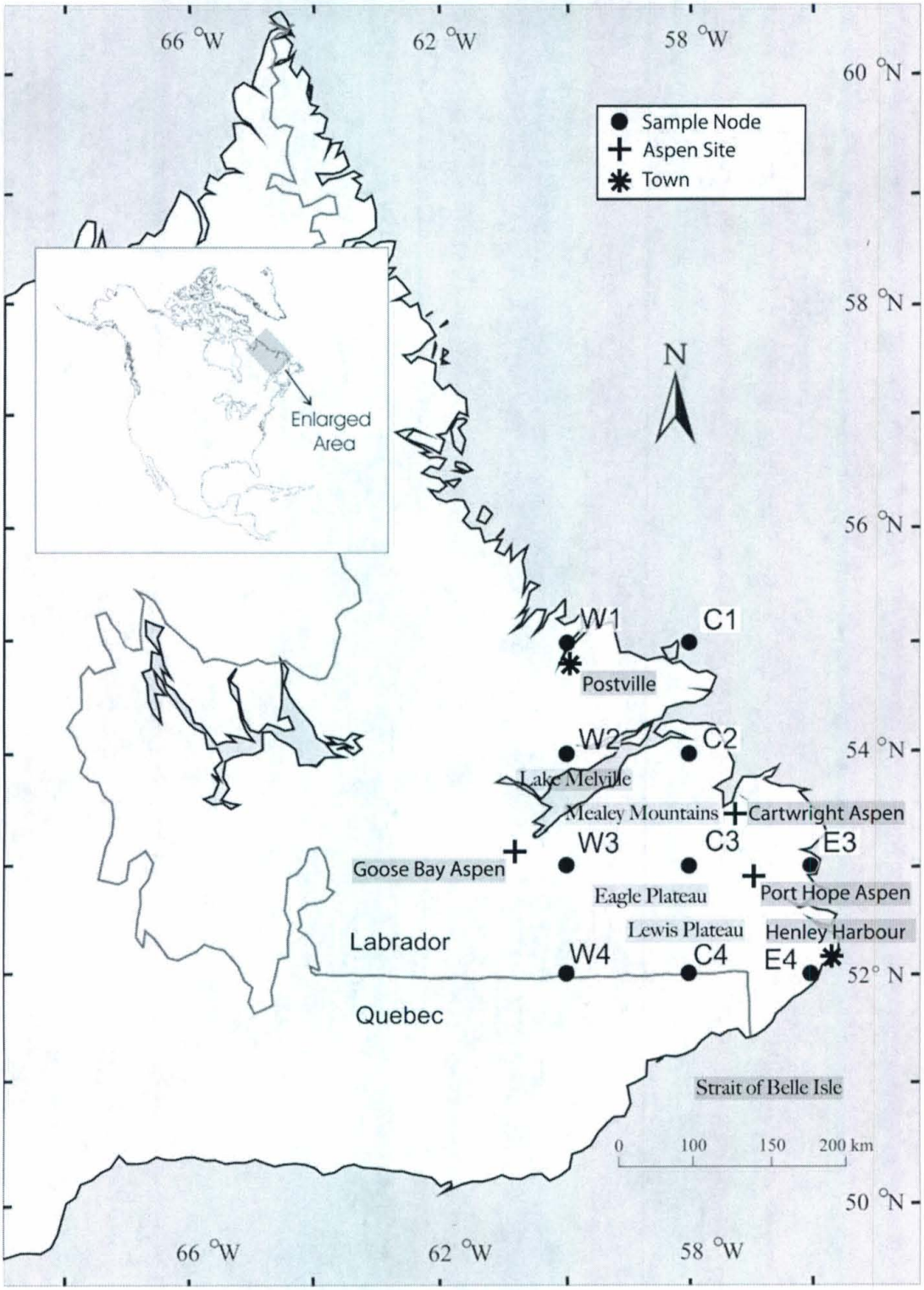

66 °W
62 °W
58 °W
60 °N
58 °N
56 °N
54 °N
52° N
50 °N
Sample Node
Aspen Site
Town
N
Enlarged Area
W1
C1
Postville
W2
C2
Lake Melville
Mealey Mountains
Cartwright Aspen
W3
C3
E3
Goose Bay Aspen
Eagle Plateau
Port Hope Aspen
Lewis Plateau
Henley Harbour
Labrador
W4
C4
E4
Quebec
Strait of Belle Isle
0 100 150 200 km

Figure 3.2

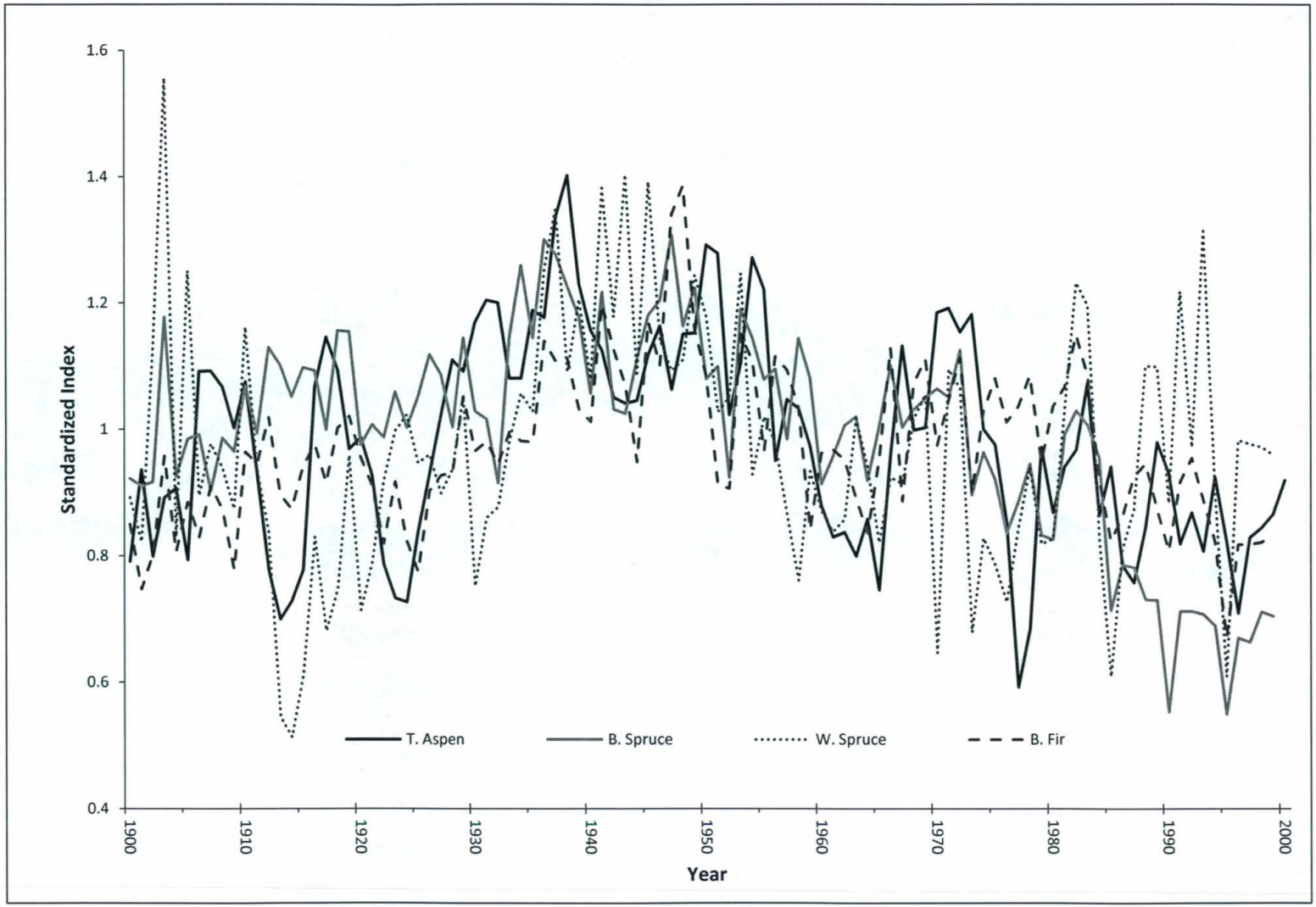

1.6
1.4
1.2
1
0.8
0.6
0.4
Standardized Index
T. Aspen
B. Spruce
W. Spruce
B. Fir
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Figure 3.3

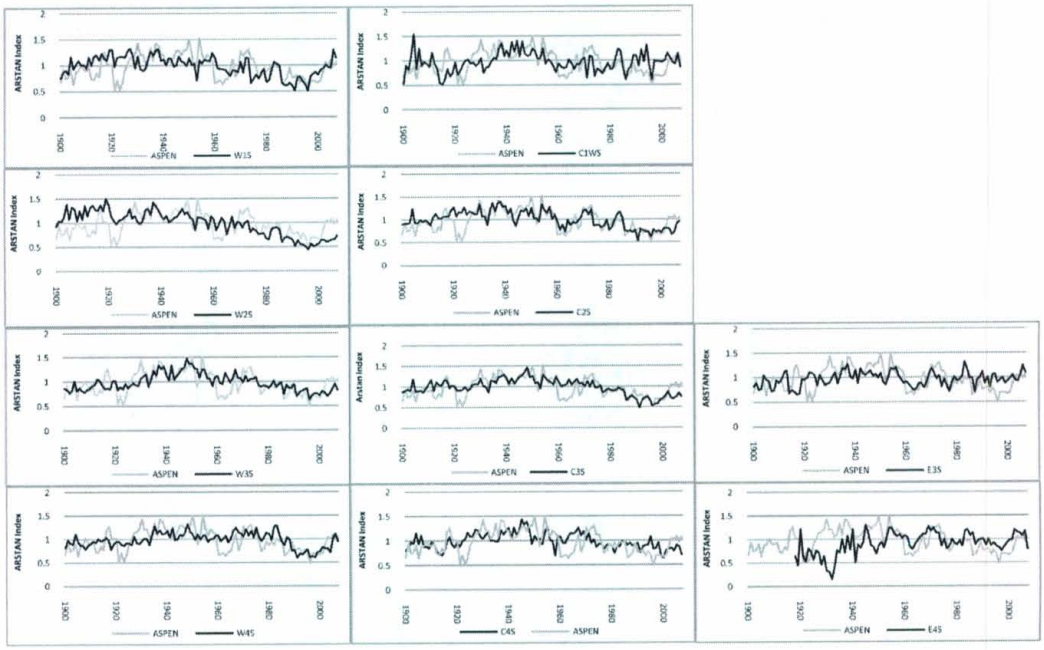


Figure 3.4a (spruce)

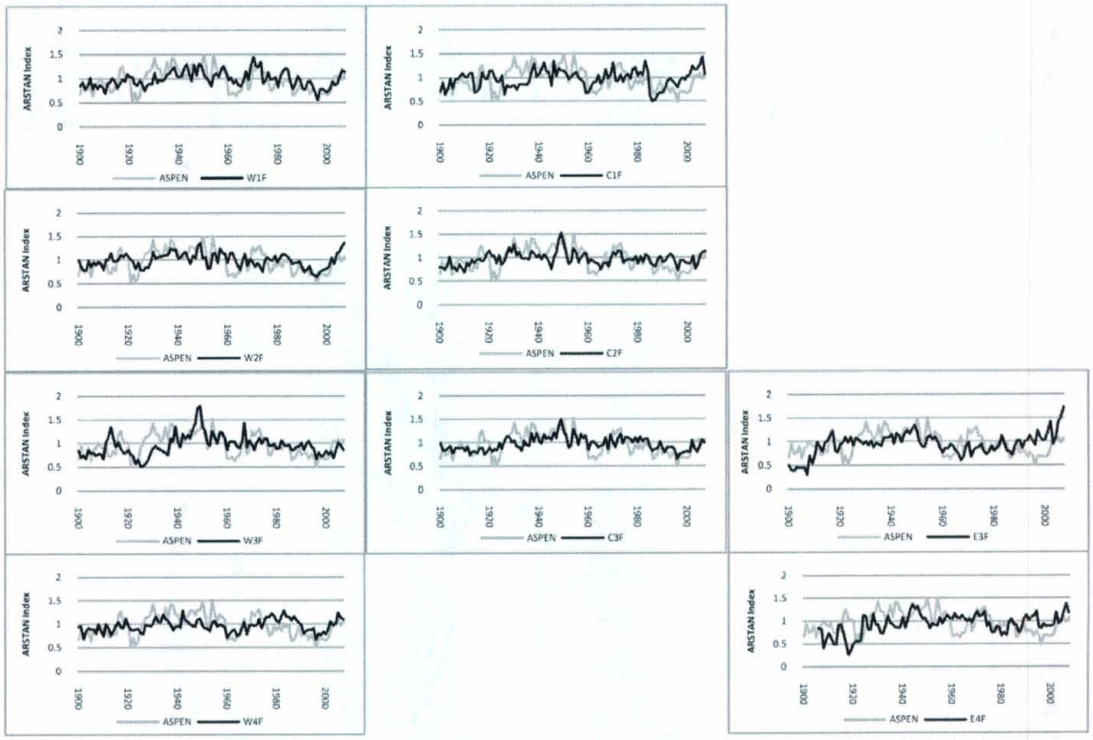
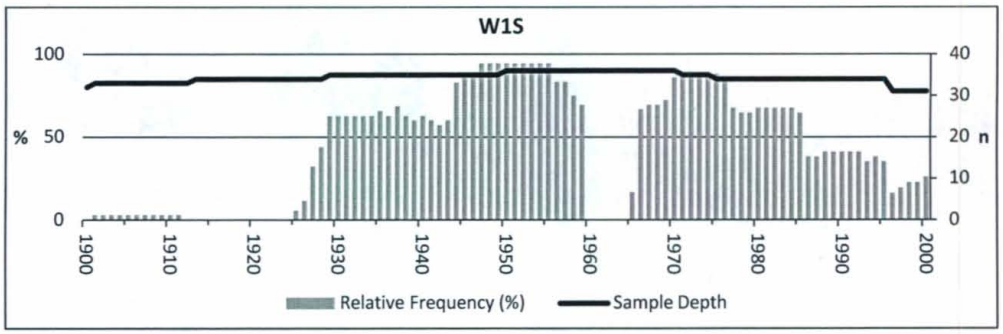
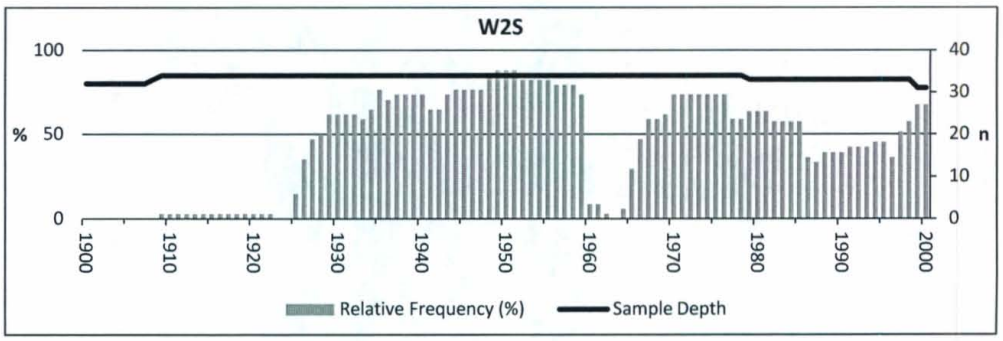
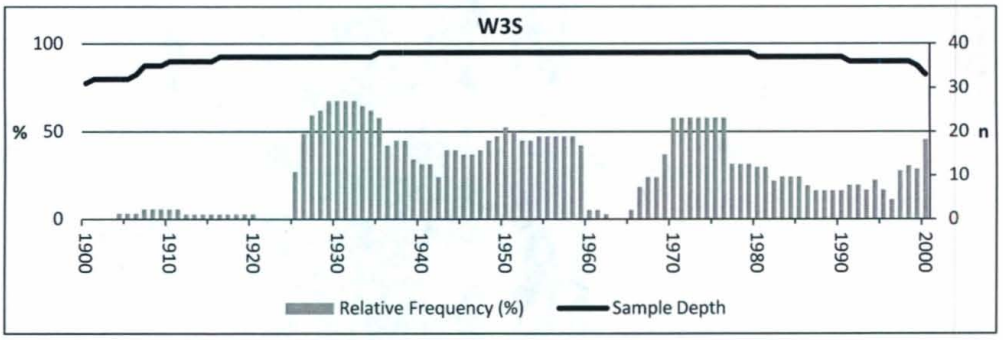
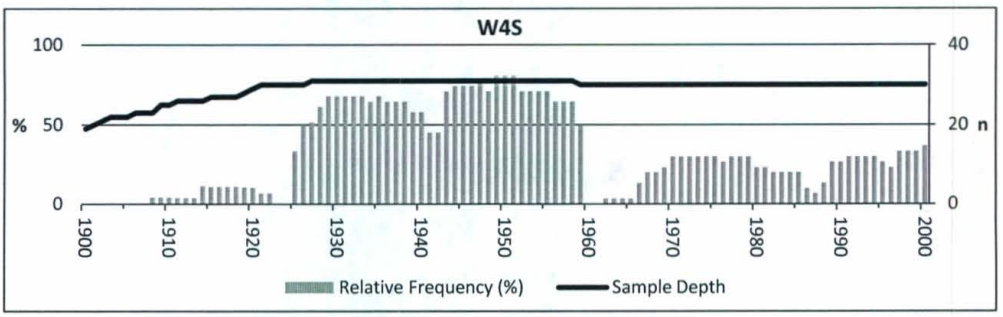


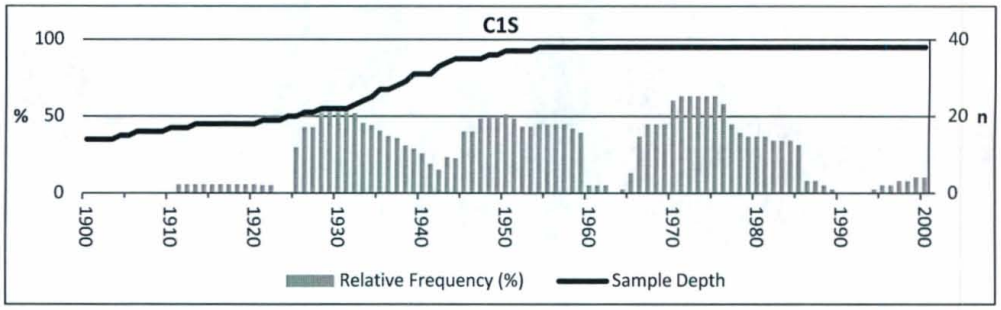
Figure 3.4b (balsam fir)

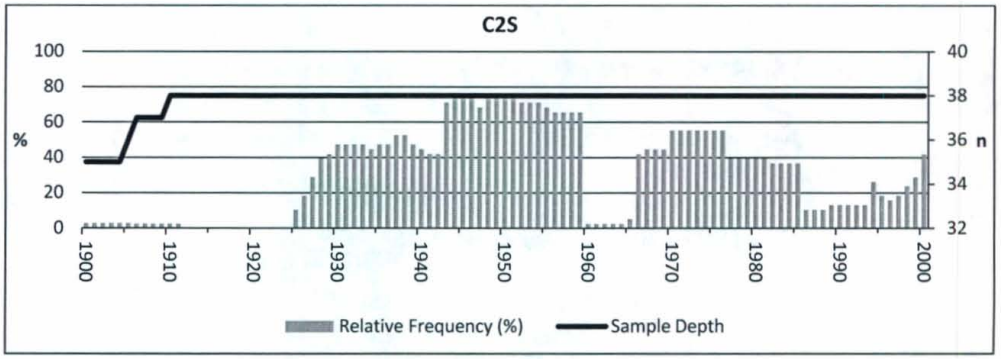

W1S
100
%
50
0
40
30
20
n
10
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth

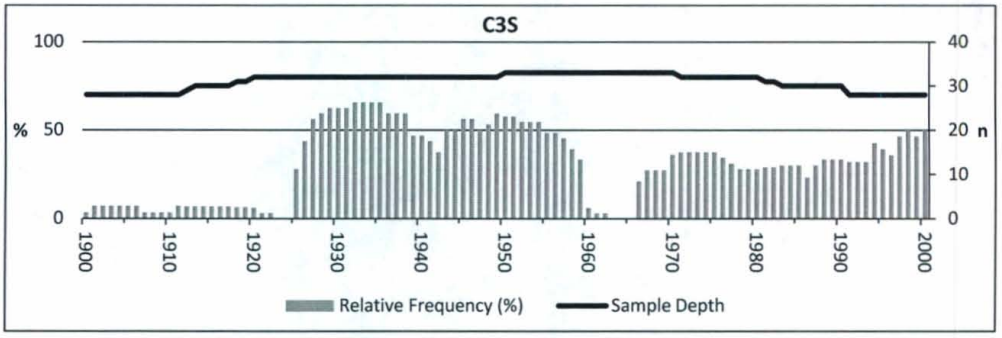

W2S
100
%
50
0
40
30
20
n
10
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth

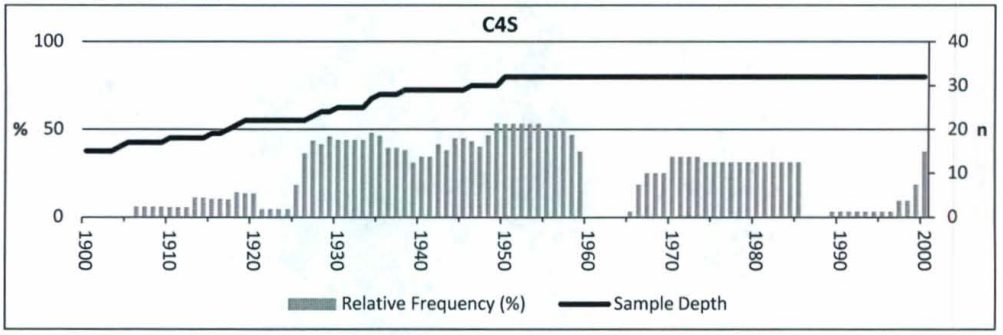

W3S
100
%
50
0
40
30
20
n
10
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth


W4S
100
%
50
0
40
20
n
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth


C1S
100
%
50
0
40
20
n
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth


C2S
100
80
60
%
40
20
0
40
38
36
n
34
32
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth


C3S
100
%
50
0
40
30
20
n
10
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Relative Frequency (%)
Sample Depth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Sample Depth

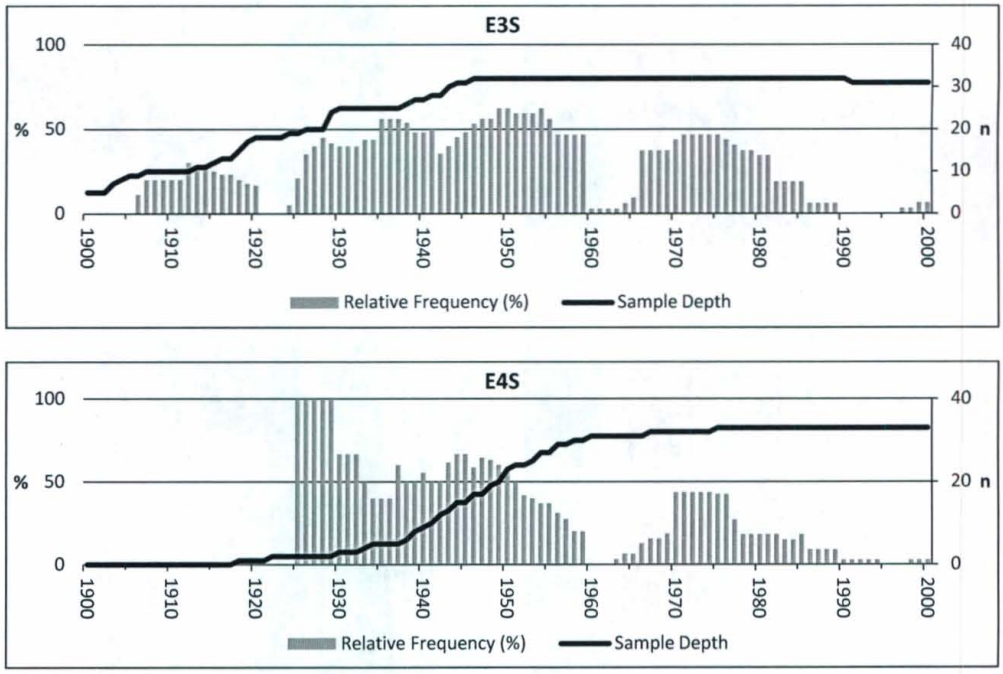
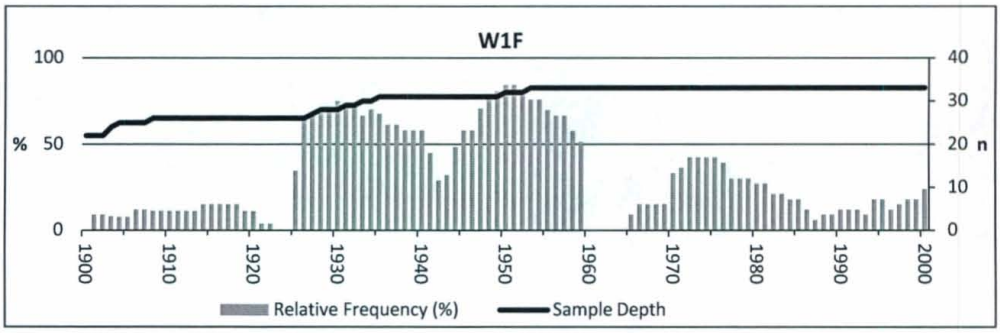


Figure 3.5a (Spruce)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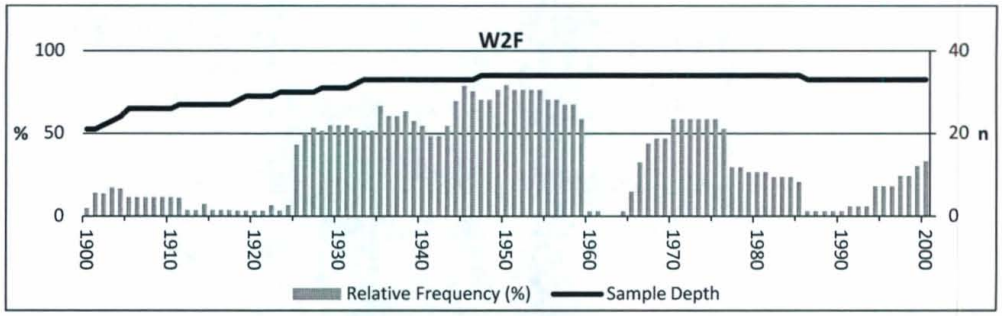
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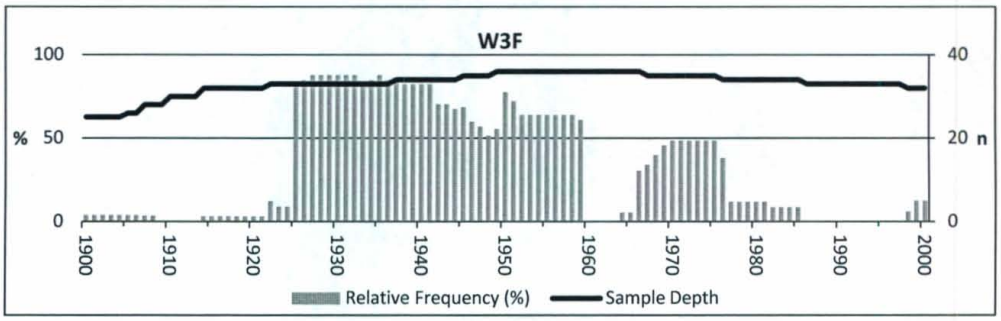
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Relative Frequency (%)
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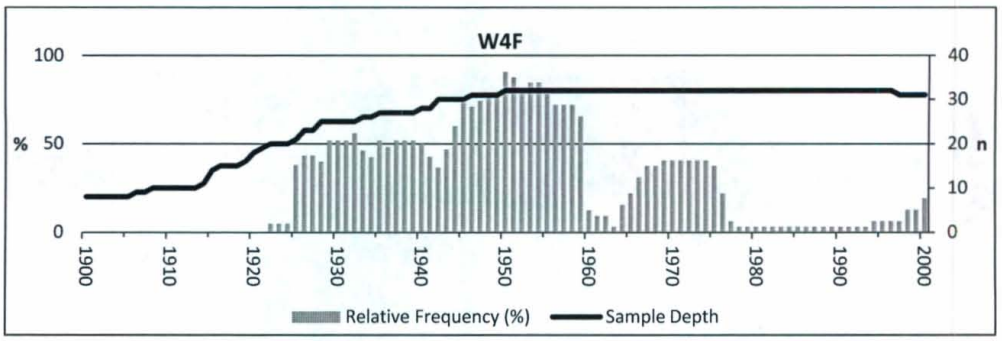
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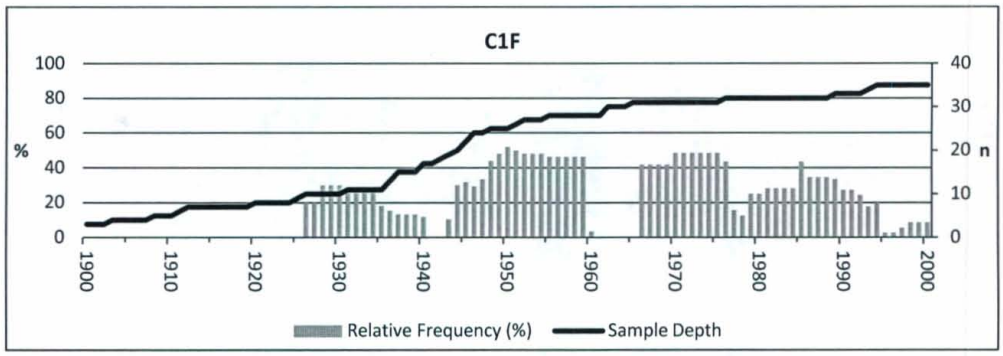
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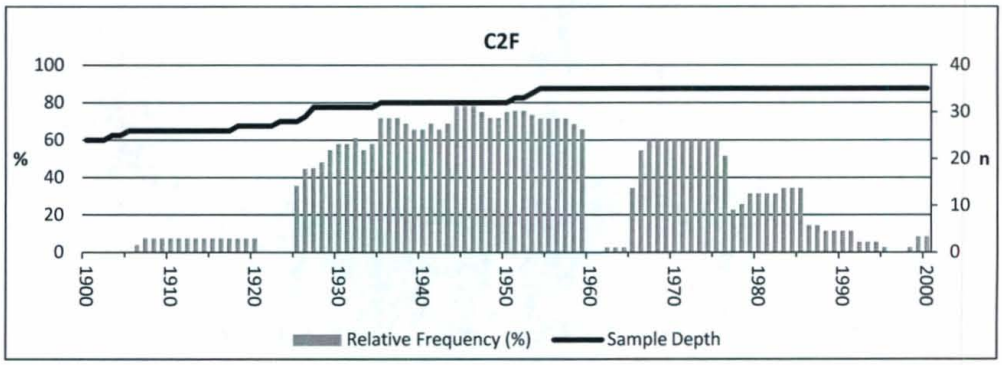
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Relative Frequency (%)
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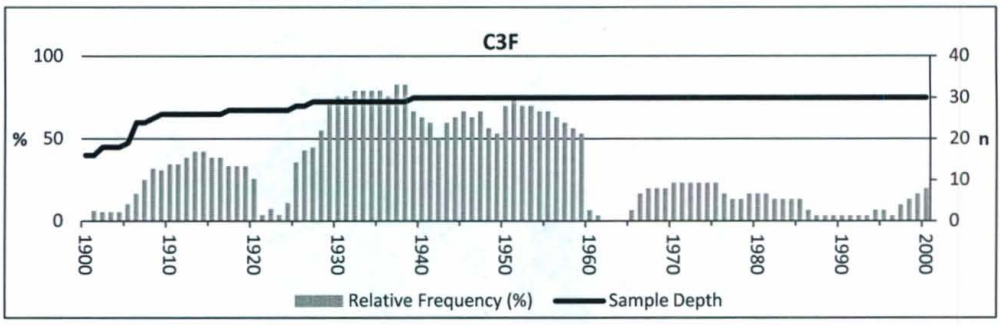
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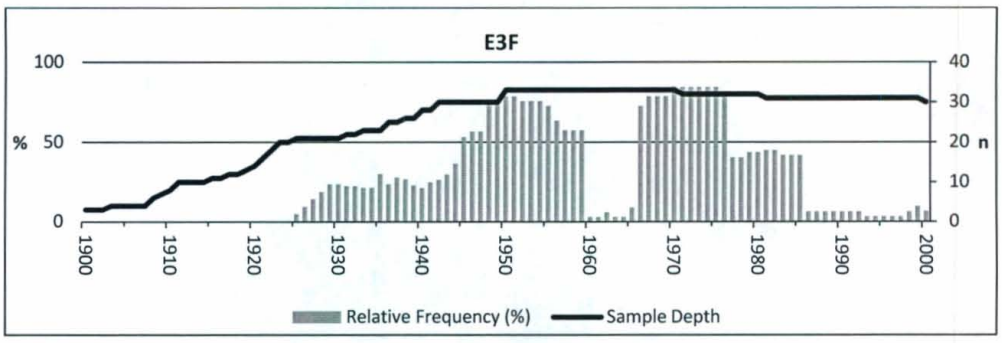
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Sample Depth

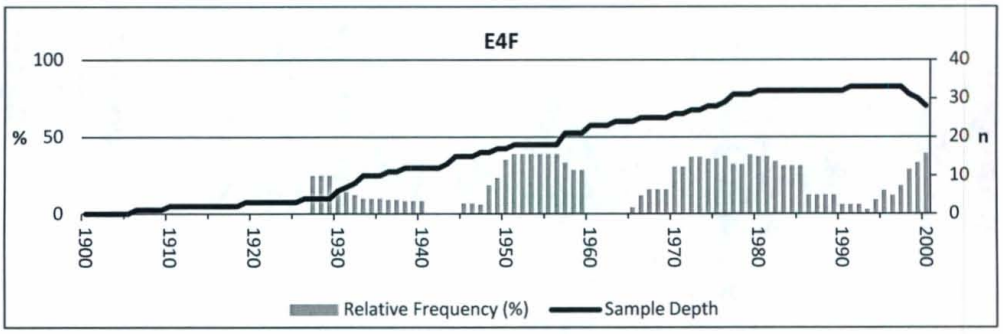

Figure 3.5b (balsam fir)

Chapter Four

Conclusions

4.1. Radial Growth-Climate Relationships in Eastern Labrador

Eastern Labrador contains four distinct zones of radial growth-climate sensitivity. All of these zones are defined by a strong correlation to July temperatures but distinctions can be found in the details of the remaining growing season characteristics. In the central region of Labrador moving toward the eastern the area of sample grid established in this study, the 'maritime zone' is distinguished exclusively by radial growth response to July temperature. In the extreme eastern portion of the study grid, where cool onshore winds come off the Labrador Sea (Roberts et al. 2006), and trees are blanketed more often under fog (Trindade et al. 2011), there is a shift in sensitivity into a defined 'hyper-maritime zone'. This zone also exhibits a strong sensitivity to July temperatures, but the defining characteristics of this coastal effect are a prolonged growing season into September, caused by the moderating effect on "summer" temperatures of the adjacent Labrador Sea. To the north the 'subarctic maritime zone' is defined by a dominance of white spruce and a growing season commencing in June. Also present is eastern Labrador is an 'upland maritime zone' which is similar to the 'hyper-maritime zone' with an extended growing season, but it is distinct due to its higher elevation away from the coast, a stronger radial growth relationship to July temperatures and a strong presence of eastern larch (*Larix laricina* (Du Roi) K. Koch) rather than balsam fir (*Abies balsamea* (L.) Mill).

4.2. Radial Growth-Climate Relationships In Greater Labrador

Fundamental to the radial growth of most of Labrador's coniferous trees is a sensitivity to July temperatures. Nishimura and Laroque's (2011) defined 'continentality' in the far western portions of Labrador diverges from this with a response to the warmth of an earlier growing season. Kennedy's (2011) northern treeline study also deviates slightly from this fundamental aspect of similar radial growth with responses that are collapsed into a shortened growing season of a few months. Examples from these two studies illustrate a shift in radial growth responses while moving away from the dominating maritime zone, which defines most of Labrador.

As one might not expect, the dominating gradient that exists in Labrador is not from north to south, but instead from west to east (or inland to coastal), as the shift in radial growth responses follow the west to east heating of the landscape, denoting a later growing season that corresponds to the shape and proximity of the coast. The western extreme of Labrador experiences an optimum growing season that occurs earlier than July (Nishumura and Laroque 2011), while the eastern extreme of Labrador has an optimum growing season that starts in July, but reaches until well past August. A north-south gradient does exist, although it is largely resigned to high latitude tree line (Kennedy, 2011).

4.3. Spruce Budworm In Eastern Labrador

In eastern Labrador, the 20th century bore three severe budworm outbreaks; the first in the 1930s, the second in the 1950s and the last in the 1970s. The 1950s was a particularly

devastating outbreak that affected the entire western and central portions of the defined study grid. The two other noted outbreaks were less severe, and the effects were concentrated more heavily in the northwest portions of the study grid.

Budworm food preference in the western and central portions of the study grid does not necessarily follow the classic species preference as seen in other regions of the boreal forest (Blais 1983). In more northern regions of the study grid, white and black spruce had a greater rate of infestation than balsam fir, the usual primary host. This is most likely a result of the increased dominance of white spruce (Kennedy 2011), and the thinning of the balsam fir population due to the proximity to its northern limit of 45°N (Roberts et al. 2006). This mixed with the dendroclimatological results in the eastern extremes of the study grid (which illustrate shifts in the radial growth-climate sensitivities in conifer trees), raises questions regarding the effects of climate change on future budworm outbreak frequencies and spatial trends.

4.4. Spruce Budworm In Greater Labrador In Relation To Eastern Canada

The addition of trembling aspen as a spruce budworm non-host species in Labrador provided the desired robust analysis that was needed to reinforce Nishimura's (2009) findings in western Labrador that were made without a non-host species. In a sense, it also validates Nishimura's regional average methodology. The outbreaks identified by Nishimura (2009) were found to extend past the boundaries of his study, into contiguous areas of central and eastern Labrador covered by portions of the gridded network of this

study. This evidence suggests that major spruce budworm outbreaks are commonly affecting all of Labrador in a synchronous way when they do occur.

The regional synchronicity of past spruce budworm outbreaks in eastern Canada (e.g. Raske and Alvo 1986, Blais 1983, Simard and Payette 2001) is also present spanning through Labrador and dissipating towards the eastern coast. Major events in the 1950s and 1970s, two substantial outbreaks in all eastern boreal regions, seem to be present in Quebec (Boulanger and Arseneault 2004), and then span eastward into the Maritimes (Ostaff and MacLean 1995), and also into Labrador (Nishimura 2009). This thesis helps identify the temporal and spatial dispersal of budworm populations eastward into Labrador up to the coast. What this study was also able to shed light on, is the lack of evidence of any movement of budworm infestations northward from the northern peninsula of Newfoundland. That said, the shift in conifer tree responses to climate along the coast of the Labrador Sea and the Strait of Belle Isle (with no viable non-host species following the same radial growth trends as the host species in this region), provides an avenue for further investigation into past budworm outbreaks in the newly delineated 'hyper-maritime zone'.

4.5. References

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